Departamento:
Ciencias Agrarias y del Medio Natural

Programa de Doctorado:
Ciencias Agrarias y del Medio Natural

Tesis Doctoral

GESTIÓN AVANZADA DEL RIEGO POR ASPERSIÓN EN PARCELA: APLICACIÓN EN EL VALLE MEDIO DEL EBRO

Memoria presentada por:
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en satisfacción de los requisitos
para optar al grado de doctor por la
Universidad de Zaragoza

Directores: Dra. María Valvanera Zapata
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Zaragoza, Noviembre de 2012

A todos aquellos que han hecho posible este trabajo

À tous ceux qui ont fait possible ce travail

For all those who made this work possible

AGRADECIMIENTOS

Un trabajo de investigación es siempre el fruto de una larga y laboriosa colaboración de todo un equipo. Por ello, me gustaría empezar esta memoria recordando a todos aquellos que han hecho que este trabajo sea posible. Reciban mi más sincero agradecimiento:

Dra. Nery Zapata Ruiz directora de esta tesis, de cuyas enseñanzas y ejemplo en el trabajo he adquirido unos conocimientos científicos, técnicos y humanos fundamentales para mi desarrollo profesional y personal.

Dr. José María Faci González, director de esta tesis, por la magnifica orientación y apoyo cuando ha sido necesario. Su rigor y su disponibilidad me han permitido terminar este trabajo a tiempo y con mucho aprovechamiento.

Un especial agradecimiento al Dr. Antonio Martínez-Cob, nuestro experto en Agrometeorología, por ofrecernos siempre su asesoría en cuanto a los temas agro-meteorológicos y por su disponibilidad para aclararnos todas las dudas sobre las variables climáticas usadas para el desarrollo de esta tesis.

A todos los miembros de mi grupo de investigación "Riegos, Agronomía y Medioambiente" sin excepciones, y sobre todo a los Doctores Ramón Aragüés, Enrique Playán, Daniel Isidoro, Farida Dechmi, Sergio Lecina, José Cavero, Ramón Isla, y Lola Quilez.

Al personal de laboratorio y de campo de la Unidad de Suelos y Riegos y por su ayuda en gran parte de los trabajos de campo y especialmente a Miguel Izquierdo, Jesús Gaudó, Juan Manuel Acín y Ricardo Santolaria.

A las comunidades de regantes de Candasnos (Antonio) y Almudevar (Felipe, Javier y Nati) cuya ayuda ha sido decisiva en el desarrollo de esta tesis.

I wish to acknowledge the hospitality of Dr. Terry A. Howell in the USDA-ARS-CPRL and all his help and advice. Thanks also are given to Dr. Steven Evett, Dr. Judy Tolk, Dr. Jairo Hernández, Maggie Gonzalez and Karen Copeland for their advice and friendly welcome.

A mis amigos del campus de Aula Dei: Ahmed, Taher, Ramzi, Sofiane, Wided, Nacho S., Raquel A., Raquel S., Walid, Ilyes…

A mis amigos de siempre, Aymen, Yousri, Riad, Omar, Walid, Jemil y Ahmed, con los que he compartido penas y alegrías durante 30 años de vida, que aunque no estén aquí conmigo en España, siempre han estado a mi lado con sus llamadas y correos electrónicos.

Finalmente, a quien más debo agradecer es a mi familia.

Para mi madre **SOUAD**, por su comprensión y ayuda en momentos malos y menos malos. Me han enseñado a encarar las adversidades sin perder nunca la dignidad ni desfallecer en el intento. Me han dado todo lo que soy como persona, mis valores, mis principios, mi perseverancia y mi empeño, y todo ello con una gran dosis de amor y sin pedir nunca nada a cambio.

Para mi mujer **RIFKA**, a ella especialmente le dedico esta Tesis. Por su paciencia, por su comprensión, por su empeño, por su fuerza, por su amor, por ser tal y como es, ... porque la quiero. Es la persona que más directamente ha sufrido las consecuencias del trabajo realizado. Realmente ella me llena por dentro para conseguir un equilibrio que me permita dar el máximo de mí. Nunca le podré estar suficientemente agradecido. Muchas gracias de todo corazón.

A ellas va dedicada esta tesis.

"Lo mejor de la vida es que mientras vivamos, tenemos el privilegio de crecer"
Joshua Loth Liebma

Esta tesis ha sido realizada en la Unidad de Suelos y Riegos (Unidad Asociada EEAD-CSIC) del Centro de Investigación y Tecnología Agroalimentaria de Aragón (CITA-DGA) y se ha desarrollado gracias a una beca del programa FPI-MINECO y los proyectos de investigación "Gestión avanzada del riego por aspersión en parcela" (AGL2007-66716-C03-01/02) y "Riego por aspersión: aplicación del agua, agronomía y flujos de retorno" (AGL2010-21681-C03-01/03) del Ministerio de Economía y Competitividad español.

RESUMEN

Esta tesis se ha enfocado principalmente al estudio de la calidad del riego por aspersión en los regadíos de Aragón (España). Los trabajos de la tesis contemplan un amplio rango de estudios del riego por aspersión que van desde la evaluación de la distribución del agua de un aspersor aislado hasta la gestión del riego en comunidades de regantes. Se han evaluado las posibilidades que ofrecen las nuevas tecnologías y los nuevos desarrollos en la gestión del riego.

En primer lugar se evaluó la curva de distribución radial de un nuevo aspersor de impacto con boquillas de plástico "RC130-BY", con varios diámetros de la boquilla principal y trabajando a varios presiones. Las curvas radiales (Rad) de este aspersor se obtuvieron al aire libre en condiciones de viento en calma ($U \leq 1$ m s^{-1}) y se compararon con las de otros modelos de aspersores de impacto utilizados en el valle medio del Ebro. Esta comparación mostró que el modelo de aspersor tiene un efecto importante sobre la distribución del agua de riego y, aunque se den las mismas condiciones ambientales y de funcionamiento, la distribución radial varía de un aspersor a otro. También se evaluó este aspersor de impacto en una cobertura total enterrada a un marco cuadrado de 18 m x 18 m para determinar el Coeficiente de Uniformidad de Christiansen (CUC) y las Perdidas por Evaporación y Arrastre (WDEL) para diferentes combinaciones de diámetros de la boquilla, presión de funcionamiento y distintas condiciones de viento. Estos indicadores de calidad de riego obtenidos con el aspersor RC130-BY se compararon con los obtenidos en campo y simulados con el modelo de simulación "Ador-Aspersión" para el mismo modelo de aspersor con boquillas de bronce (RC130-L). Para condiciones medias de viento (1,5 m $s^{-1} \leq U \leq 4{,}0$ m s^{-1}) el CUC del aspersor RC130-BY fue menor (promedio de 78%) que del aspersor RC130-L (promedio de 87%). Los resultados del trabajo muestran que este tipo de herramientas y análisis permiten decidir las combinaciones más convenientes del modelo de aspersor, diámetro de boquillas y presión de trabajo a fin de optimizar la uniformidad y la eficiencia del riego por aspersión.

Se ha puesto un especial énfasis en el análisis de las pérdidas brutas por evaporación en riego por aspersión (SEL_g) y en determinar cual es la contribución de estas pérdidas a la disminución de la evapotranspiración del cultivo (ET) durante y después del riego por aspersión. Para ello se han efectuado medidas simultáneas de la ET en dos lisímetros de pesada instalados en dos parcelas cultivadas de alfalfa (Medicago sativa L.), una se regaba durante las medidas (tratamiento regado, MT) y la otra no se regaba (tratamiento seco, DT). Ambas parcelas se regaron con una cobertura fija de riego por aspersión aplicando una cantidad suficiente de agua para cubrir las necesidades hídricas del cultivo durante toda la campaña. Los resultados mostraron que las pérdidas netas por intercepción (IL_n) estuvieron moderadamente relacionados con el déficit de presión de vapor (DPV). Las pérdidas netas de evaporación (SEL_n) fueron de 8,3% del total de agua aplicada, algo inferiores a las pérdidas brutas por evaporación y arrastre ($WDEL_g$). Se encontró que las pérdidas netas de evaporación (SEL_n) eran principalmente una función de la velocidad del viento.

Se ha efectuado un análisis detallado de la gestión del riego en dos comunidades de regantes con riego presurizado, una de ellas con presión natural (Comunidad de errantes de Candasnos, CID) y la otra con presión forzada (Comunidad de Regantes de Almudevar, AID). La Comunidad de Regantes de Candasnos (CID) es una comunidad de riego presurizado equipada con un sistema de telecontrol. Los datos del telecontrol y los cálculos de las necesidades hídricas de los cultivos, nos han permitido analizar la calidad del riego en la CID para los cultivos mayoritarios (maíz, alfalfa y melocotonero) mediante el estudio de la evolución temporal del Índice Estacional de la Calidad de Riego (SIPI). Por otro lado, el seguimiento continuo de la presión mediante transductores de presión instalados en aspersores de los sistemas de riego de 10 parcelas de cobertura total permitió estudiar las pautas de riego utilizadas en las coberturas fijas de la CID. Los promedios de SIPI para el maíz, alfalfa y melocotonero fueron de 83%, 107% y 123%, respectivamente. Estos valores son indicativos de una eficiencia razonablemente buena en la zona regable. Se encontraron dos pautas generales del manejo

del riego en la CID: la primera se caracterizó por una mínima modificación del calendario de riego y la segunda se caracterizó por los cambios semanales en el calendario de riego. La segunda pauta es la más frecuente para los sistemas de cobertura fija. En general se encontró un buen uso del agua de riego en la CID si bien se detectó una alta frecuencia de riegos que puede ser causa de altas pérdidas por intercepción por los cultivos. En general se ha encontrado un buen manejo del riego en la CID, sin embargo, los riegos cortos y frecuentes detectados sobre todo para el cultivo de maíz pueden ser una causa de altas pérdidas por intercepción.

La comunidad de regantes de Almudevar (AID), tradicionalmente regada por superficie, se transformó en riego presurizado a finales del 2010. Las parcelas se equiparon con sistemas de riego por aspersión y con un sistema muy avanzado de telemetría y control remoto que llega a controlar hasta las válvulas de sector de las parcelas. Esta particularidad le permite no sólo realizar una gestión centralizada del riego sino ejecutarla desde la oficina de la comunidad. La comparación entre el antes y después de la modernización de riego se realizó en términos de estructura parcelaria, patrones de cultivo y manejo del riego. Con los datos obtenidos del sistema de telemetría durante la campaña 2011 se analizó la evolución temporal del uso del agua y de la energía y la adecuación de la demanda energética a la potencia contratada. En el análisis del uso del agua y de la energía se realizó especial énfasis en los meses de mayor demanda (Julio y Agosto). Se determinó el Índice Estacional de Calidad de Riego (SIPI) para una frecuencia mensual y estacional y para los cultivos principales en la comunidad de regantes. El SIPI mostró un valor medio global de 95% y una variación espacial y temporal importante. El promedio de SIPI osciló entre 88% en el maíz hasta 131% para la cebada. En general, los patrones de aplicación del riego mostraron una fuerte relación y adecuación con las tarifas energéticas debido al control centralizado de la gestión del riego. Además, el análisis mostró una infra-utilización de la potencia contratada en las cuatro zonas de gestión de riego de la comunidad, sobre todo durante el período tarifario de alto costo (P2). Se ha identificado la posibilidad de ajustar la contratación de la potencia con el fin de disminuir el coste total. La disponibilidad de datos a tiempo real del consumo de agua de riego proporcionado por el sistema de telecontrol, y la posibilidad de analizar la demanda futura, permite la optimización de la distribución de las demandas de riego en función de las posibilidades de contratación de potencia, el período tarifario y las limitaciones de la red de riego.

ABSTRACT

This thesis has focused mainly on the sprinkler irrigation performances and managements in Aragon (Spain). The work of the thesis provides a wide range of sprinkler irrigation studies ranging from the individual sprinkler operation to the water use association management. We evaluated the possibilities offered by new technologies and new developments in irrigation management.

In the first chapter, the radial distribution curve (Rad) of a new agricultural sprinkler with plastic nozzles "RC130-BY", equipped with various diameters of the main nozzle and working under several operating conditions were analyzed. The Rad of this type of sprinkler were obtained under calm wind ($U \leq 1$ m s^{-1}) in open air conditions and the resulting Rad were compared with those of other agricultural impact sprinkler with brass nozzle widely used in the middle Ebro River Valley. This comparison showed that the sprinkler model has an important effect on the irrigated water distribution and although under similar operational conditions, the radial distribution varies from one to other agricultural impact sprinkler. Also a sprinkler solid set at a square spacing 18 m X 18 m equipped with the same type of sprinkler was evaluated for uniformity (CUC) and wind drift and evaporation losses (WDEL) for different combination of nozzle diameters and operating pressures under different wind conditions. Finally the experimental CUC and WDEL of the solid set with the "RC130-BY"sprinkler were compared with the simulated values obtained experimentally and simulated with the simulation model "Ador-Sprinkler" for the same sprinkler model with brass nozzles (RC130-L) under the same operational conditions. For average wind conditions (1.5 m $s^{-1} \leq U \leq 4.0$ m s^{-1}), CUC for the RC130-BY model (average of 78%) was lower than CUC for the RC130-L sprinkler model (average of 87%). The results of this analysis showed that the type of sprinkler has an important influence on the sprinkler irrigation uniformity and that this type of analysis tools, may serve as a decision making to choose the most suitable combinations of sprinkler model, nozzle diameter and working pressure to optimize the uniformity and efficiency of sprinkler irrigation.

It was focused a special emphasis on analyzing the gross sprinkler evaporation losses (SEL_g) and how much of these SEL_g contribute to decrease the crop evapotranspiration (ET) during and after the sprinkler irrigation. For this reason, the gross WDEL ($WDEL_g$) and evapotranspiration (ET) were measured simultaneously in two alfalfa (Medicago sativa L.) plots, one being irrigated (moist, MT) and the other one not being irrigated (dry, DT). Both plots were irrigated with a solid set sprinkler system applying enough water to meet the crop water requirements during the whole season. Results showed that the net interception losses (IL_n) were moderately related to vapor pressure deficit (VPD). SEL_n were 8.3% of the total applied water and slightly less than $WDEL_g$ (8.5%). SEL_n was mainly a function of wind speed.

A detailed analysis of irrigation management has been conducted in two irrigation districts to pressurized irrigation, one with natural pressure (Candasnos Irrigation District, CID) and the other with forced pressure (Almudevar Irrigation District, AID). The Candasnos irrigation district (CID) equipped with a telecontrol irrigation system, and contains a variety of different pressurized systems. Telecontrol data and crop water requirements were used to analyze the evolution of irrigation performance (SIPI) of maize, alfalfa and stone fruits. Ten solid set farms were monitored to determine on-farm irrigation patterns. The average SIPI of maize, alfalfa and peach was 83%, 107% and 123%, respectively. The average SIPI showed good irrigation performance, however, the spatial and temporal variability of SIPI showed possibilities for improvement. Two farmer irrigation patterns were established at the CID: the first was characterized by structured irrigation schedules and the second was characterized by weekly changes in the irrigation schedule. Generally, we found a good use of irrigation water in the CID, although, the short and frequent irrigation timing for maize crop could be a disadvantageous practice since it yielded high evaporation losses from crop intercepted water.

The Almudevar irrigation district (AID), a traditional surface irrigation district, was transformed into pressurized irrigation in late 2010. The plots were equipped with sprinkler irrigation systems and with a high level telemetry and remote control system which reaches the irrigated block level and permits the centralized management of the 2200 irrigation blocks from the district office. Comparison between before and after the AID modernization was established in terms of land structure, crop patterns and irrigation management. The temporal evolution of irrigation water and energy demands in 2011 irrigation season and the adequacy of the energy demand with the contracted electric power were analyzed with the available telemetry data of 2011. The energy analysis was focused on the months of peak water demand (July and August). An irrigation performance index (SIPI) for a monthly and seasonal frequency was computed for main crops in the AID. The SIPI showed an overall average value of 95% but with a high spatial and temporal variation. The average SIPI ranged between 88% for maize to 131% for barley. In general, the irrigation patterns showed a strong relationship with the energy tariff schedule due to the centralized control of the irrigation management. Also, the energy analysis showed an infra-use of the contracted power in the four irrigation zones of the AID especially during one of the high cost tariff period (P2). The possibility of adjusting the power contracting in order to decrease the total cost has been identified. The adjustment should be considered in the irrigation organization. The availability of real time irrigation consumption data provided by the telemetry and remote controls system, and the possibility of analyzing future demands, allow the optimization of the distribution of irrigation demands in accordance with the power contracting possibilities, the tariff period of the electric bill and the irrigation network limitations.

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CAPITULO I: INTRODUCCIÓN Y OBJETIVOS

I.1. INTRODUCCIÓN GENERAL A LOS TEMAS DE LA TESIS

En las últimas décadas el crecimiento económico en España ha aumentado considerablemente la demanda de los recursos hídricos, sin embargo la disponibilidad de agua apenas ha crecido debido a la falta de incrementos significativos en la capacidad de almacenamiento de agua (M.A.R.M, 2006). El Gobierno español ha introducido varias reformas para gestionar la demanda de agua, como los bancos de derechos de agua, los impuestos ambientales y las subvenciones para la modernización de regadíos. Además, los nuevos planes de gestión del agua se están llevando a cabo a través de un proceso participativo e integrado siguiendo las pautas de la Directiva Europea Marco del Agua (Lecina y col., 2009 y 2010a). Una de las actuaciones más importantes para la gestión de los recursos hídricos es la modernización del regadío desarrollada a través del Plan Nacional de Regadíos (Horizonte 2008 y Horizonte 2015) y el Plan de Choque de Modernización de Regadíos (M.A.R.M, 2002; M.A.R.M, 2006). Los objetivos principales de estos planes son: el ahorro de agua, la transferencia de tecnología, el fomento de la utilización de recursos hídricos alternativos, la eficiencia energética, la mejora de la renta agraria, la creación de puestos de trabajo adicionales y, en general, el fomento de la sostenibilidad del regadío español (M.A.R.M, 2010). Durante los últimos años, las políticas nacionales y regionales han favorecido la modernización de las zonas regables en España.

España cuenta con alrededor de 3.473.474 ha de tierras de regadío (M.A.A.M.A, 2011), lo que representa el tercio de la superficie total del regadío en la EU-27. A nivel nacional esta superficie representa el 13% de la superficie agrícola total, genera el 60% del producto interior bruto agrícola y el 80% de las exportaciones agrícolas totales. Una hectárea de regadío puede producir hasta seis veces más que una hectárea de secano (Camacho Poyato, 2005; M.A.R.M, 2009; Maestu y Gómez, 2010). Antes de la aparición de los planes de modernización de regadíos, el riego por superficie ascendía al 59% de la superficie total del regadío, y hasta el 71% tenía infraestructuras con más de 25 años de antigüedad (M.A.R.M, 2002).

Como resultado de los procesos de modernización del regadío, el riego por aspersión está incrementando su superficie en muchas zonas de España. Según la Encuesta sobre Superficies y Rendimientos de Cultivo (ESYRCE) del año 2011 (M.A.A.M.A, 2011), el total de la superficie regada por aspersión en España asciende a 497.794 ha. La Comunidad Autónoma de Aragón es una de las comunidades que más superficie de regadío tienen en

España, se sitúa en la cuarta posición después de Andalucía, Castilla La Mancha y Castilla y León, (M.A.A.M.A, 2011). El regadío en Aragón representa el 11% del total nacional lo que supone una superficie de 382.620 ha y se caracteriza principalmente por el fuerte impulso modernizador, que en los últimos años ha incrementado la superficie de riego por aspersión desde el año 2004 hasta el 2011 en un 26% (M.A.A.M.A, 2011; IAEST, 2011). La agricultura de regadío en Aragón tiene una orientación cerealista-forrajera, con cultivos mayoritariamente herbáceos como la alfalfa y el maíz. Los proyectos de modernización de riego en esta zona han consistido fundamentalmente en la modernización integral de regadíos tradicionales de riego por superficie a riego presurizado y la transformación de secanos a nuevos regadíos con sistemas de riego a presión. Muchos de estos sistemas de riego por aspersión incorporan equipos de automatización y sistemas de vigilancia telecontrolada que sitúan a la agricultura española a la cabeza de la agricultura europea en cuanto a tecnología (M.A.R.M., 2010). Estos sistemas de telecontrol de riego son cada vez más populares en las comunidades de regantes españolas y han proporcionado nuevas posibilidades al campo de la telegestión. Los sistemas de telecontrol ofrecen datos continuos sobre el consumo de agua y de la energía asociada de riego a nivel del hidrante o en algunos casos la información puede llegar hasta nivel de sectores de riego en parcela, lo que permite caracterizar a tiempo real los indicadores de la calidad del riego, así como el uso de la energía. La calidad del riego se determina generalmente con un conjunto de indicadores específicos haciendo énfasis en los cultivos y al uso de agua (Molden y Gates, 1990; Malano y Burton, 2000; Playán y Mateos, 2006; Fernández y col., 2007). Los indicadores deben ser adaptados localmente para describir la idiosincrasia de cada zona de regadío (Lorite y col., 2004). La determinación de estos indicadores para los principales cultivos de una zona de estudio y su variabilidad entre los diferentes sistemas de riego y entre los diferentes usuarios del agua, permitirá establecer prácticas de mejora de la gestión del riego.

Los planes de modernización del regadío pretenden ahorrar 3.100 M m^3 de agua por año para paliar las consecuencias de las sequías cíclicas en otros sectores. Estos planes han invertido 7.368 M € a lo largo de esta década para mejorar las infraestructuras de riego de casi 2 M ha (M.A.R.M, 2002; M.A.R.M, 2006). Este ahorro "teórico" de agua representa el 15% del promedio anual de uso agrícola del agua en el ámbito nacional. Estas perspectivas de ahorro de agua se basan especialmente en la reducción del consumo de agua de riego debido a las mejoras esperadas de la eficiencia del riego en las explotaciones agrícolas, sin embargo según estudios recientes de Lecina y col., (2010b) en la Comunidad General de

Riegos del Alto Aragón (RAA), la modernización de regadíos orientada al incremento de la productividad agraria, supondrá un incremento de la evapotranspiración productiva de los cultivos (ET) a la que se sumará el incremento de la no productiva como consecuencia de las pérdidas por evaporación y arrastre (WDEL, según el acrónimo en Ingles) y por lo tanto un incremento en el consumo de agua.

El riego por aspersión ha sido ampliamente utilizado en todo el mundo por su fácil manejo, su elevada eficiencia potencial en la aplicación del agua, su aumento de la productividad de los cultivos y el bajo impacto ambiental que ocasiona. El uso eficiente del agua es uno de los mayores retos actuales y futuros en la agricultura de regadío donde el agua es un recurso escaso. Según Clemmens y Dedrick (1994), la eficiencia del riego por aspersión puede situarse entre el 70 – 85 % en el caso de coberturas totales y entre el 75 – 90 % en el caso de pivotes y máquinas de avance frontal. Sin embargo, estos sistemas no funcionan siempre a su eficiencia potencial máxima, debido a un manejo inadecuado, a un diseño incorrecto y a condiciones meteorológicas no siempre favorables, especialmente el viento, durante el riego

Un elevado porcentaje de las comunidades de regantes del Valle Medio del Ebro se encuentran en zona catalogada como ventosa por Martínez-Cob y col., (2010). La velocidad media del viento a 2 m por encima del nivel del suelo en esta zona es superior a 2 m s^{-1} (Puicercús y col., 1994; Hernández Navarro, 2002; Martínez-Cob y Tejero, 2004; Martínez-Cob y col., 2010). El conocimiento de las condiciones del viento local es un tema vital para hacer un buen manejo del riego por aspersión. La velocidad del viento, presenta en general un patrón de comportamiento distinto en el día y la noche, que se manifiesta con claridad en el Valle del Ebro (Playán y col., 2005). El viento durante las horas diurnas es sensiblemente mayor que durante la noche. Así, de media se puede establecer que en el Valle del Ebro la velocidad del viento diurno es 2 veces el viento nocturno (Martínez-Cob y col., 2010).

Cuando el riego por aspersión se realiza en condiciones de viento moderado o fuerte, la eficiencia disminuye debido a una mayor pérdida por evaporación durante el viaje de las gotas de agua hacia el suelo y arrastre fuera de la zona cultivada y a una menor uniformidad (Tarjuelo, 1995; Playán y col., 2005; Martínez-Cob y col., 2010). Las WDEL son uno de los mayores inconvenientes del riego por aspersión. En condiciones de vientos frecuentes y de cierta intensidad, caso del Valle Medio del Ebro, estas pérdidas pueden alcanzar valores de hasta el 30% (Faci y Bercero, 1991) si el riego no se maneja de forma adecuada. Un buen manejo del sistema puede reducir estos elevados valores de WDEL a valores entre un 10% y un 20% (Playán et al. 2005), aunque en la literatura se encuentran valores entre el 2 y el 40 % (Yazar, 1984; Kohl y col., 1987; Seginer y col., 1991, b; Kincaid, 1996; Kincaid y col., 1996; McLean y col., 2000). Se han observado diferencias importantes en las WDEL según el sistema de riego (Schneider y Howell, 1995; Tarjuelo y col., 2000; McLean y col., 2000). En Aragón, Playán et al. (2006) obtuvieron valores de WDEL del 12,1% en sistemas de cobertura total frente a 6,6% en máquinas de riego.

Las pérdidas por arrastre constituyen entre el 40 y el 60% del total de las WDEL (Kraus, 1966; Sternberg, 1967; Kohl y col., 1987; Tarjuelo, 1995).Varios estudios han mostrado que las pérdidas por evaporación dependen de la humedad relativa del aire, de la temperatura del aire y del agua del riego, de la velocidad del viento, de la altura de los emisores, de la presión de funcionamiento y del diámetro de las gotas emitidas (Abo-Ghobar, 1993; Lorenzini, 2002; Lorenzini, 2004; De Wrachien and Lorenzini, 2006; Bavi et al. 2009). En cuanto a las pérdidas por arrastre, están determinadas principalmente por la velocidad del viento, el diámetro de las gotas y la altura de vuelo (Edling, 1985; Tarjuelo, 2000; Martínez-Cob y col., 2008)

La mayoría de las pérdidas del agua en el riego por aspersión se producen durante el desarrollo del riego, a excepción de las pérdidas por evaporación del agua interceptada por el cultivo (IL) (Steiner y col., 1983a), proceso que acontece durante el riego y con mayor intensidad en las horas siguientes a la finalización del riego. En cuanto a las IL, varios autores indican que estas perdidas dependen en gran parte en la arquitectura de las hojas, del tipo de hojas y del estado vegetativo de las plantas (Norman y Campbell, 1983; Steiner y col., 1983b). Como consecuencia de las WDEL y de las IL durante y después del evento de riego, se modifican las condiciones microclimáticas, produciéndose un descenso del déficit de presión de vapor (DPV) así como de la temperatura del aire (Robinson 1970; Steiner y col. 1983b; Tolk y col., 1995). Este descenso en el déficit de presión de vapor (DPV) contribuye a la reducción de la transpiración del cultivo (T) y puede favorecer la conservación de agua en el suelo que a su vez, puede contribuir a la evapotranspiración (ET) del cultivo. Estos cambios microclimáticos durante el riego por aspersión pueden durar hasta varios días después del evento del riego (Kraus, 1966; Kohl y Wright, 1974; Longley y col., 1983), aunque en general en nuestras zonas semiáridas estos cambios se reducen a unas pocas horas después del riego (Martínez-Cob y col., 2008). Los cambios microclimáticos durante el riego por aspersión, causan también cambios fisiológicos en el cultivo que son más importantes en los sistemas de riego por cobertura fija de aspersión porque el tiempo de riego es mayor que en el caso de los pívots y máquinas de riego (Cavero y al., 2009). Los cambios microclimáticos y fisiológicos son más relevantes durante eventos de riego diurno que durante eventos nocturnos debido a los mayores valores de temperaturas, DPV del aire y actividad fisiológica de las plantas (Cavero el al., 2009).

Burt y col., (1997) clasifican las pérdidas WDEL e IL como consuntivas no beneficiosas. Sin embargo, McNaughton (1981), afirma que la parte de estas perdidas que reemplaza o contribuye a la evapotranspiración del cultivo (ET) debe ser considerada como consuntiva y beneficiosa. Por esta razón, McNaughton 1981 y Martínez-Cob y col., 2008, indican la necesidad de definir los conceptos de WDEL brutos y netos durante el riego por aspersión ($WDEL_g$ y $WDEL_n$, respectivamente) y las IL brutos y netos después de riego por aspersión (IL_g e IL_n, respectivamente). Las $WDEL_g$ y las IL_g correspondan a las pérdidas totales en riego por aspersión, incluidas las que contribuyen a la reducción de la ET, mientras que las $WDEL_n$ y las IL_n corresponden a las pérdidas reales, que se obtienen de restar a las pérdidas brutas la contribución a la ET del cultivo. Considerar las pérdidas brutas en vez de las pérdidas netas como pérdidas reales, supone un error en el cálculo de la eficiencia del riego (Martínez-Cob y col., 2008). De estos trabajos se desprende la importancia de evaluar las pérdidas netas en riego por aspersión para diferentes cultivos y a diferentes escalas, de parcela y de comunidad de regantes. Martínez-Cob et al., 2008 y Cavero et al., 2009 apuntan a que tanto las pérdidas por intercepción como los cambios microclimáticos pueden verse muy afectados no sólo por las condiciones meteorológicas del riego, sino también por el porte del cultivo. La mayoría de los trabajos que cuantifican las WDEL en el riego por aspersión hacen referencia a las pérdidas brutas. En esta tesis se contribuye al conocimiento y al avance de la cuantificación de las $WDEL_n$ en el cultivo de la alfalfa, cultivo muy importante en el Valle del Ebro.

En las últimas décadas, se han introducido cambios tecnológicos importantes en los sistemas de riego por aspersión que han permitido mejorar la calidad del riego, disminuir las pérdidas de agua, aumentar el rendimiento de los cultivos y mejorar las eficiencias de las tareas del regadío. En el valle del Ebro, el suministro de agua a los sistemas de riego por aspersión se basa en el uso de redes colectivas que garantizan a los regantes individuales un conjunto de condiciones de acceso al agua de riego. La estructura parcelaria fragmentada de las comunidades de regantes en esta zona, caracterizadas por presentar un gran número de parcelas de pequeño y mediano tamaño, ha favorecido la instalación de sistemas de cobertura total enterrada con muy poca presencia de máquinas de riego, más adaptadas a superficies medianas y grandes.

En riego por aspersión la elección del modelo de emisor más conveniente depende de la configuración del marco de aspersión, su forma y espaciamiento, las necesidades de riego y la sensibilidad de los cultivos al estrés hídrico y al encharcamiento, la capacidad de infiltración del suelo y la capacidad de la red colectiva de riego (Sánchez et al., 2011). En general, en las coberturas totales de riego por aspersión del Valle Medio del Ebro, se utilizan aspersores de impacto metálicos equipados con doble boquilla de bronce roscada en el cuerpo del aspersor. Como pieza aparte insertada en el cuerpo del aspersor como continuación de la boquilla principal, está la vaina prolongadora. Esta pieza de forma cilíndrica tiene en su interior unos dientes paralelos a la dirección del chorro que tienen la función de acelerar el chorro para que llegue más lejos. Cuando estas boquillas se obstruyen es necesario utilizar una herramienta para desenroscarlas y limpiarlas. Muchas veces esta tarea es complicada ya que los aspersores se instalan a 2 m del suelo y la vaina prolongadora del chorro, como pieza aparte, puede perderse durante este proceso. Con el fin de evitar estos problemas, algunas empresas de riego por aspersión han desarrollado boquillas de plástico que se pueden quitar e insertar fácilmente en los aspersores solo con la mano y con un simple giro de la boquilla de 90º (¼ de vuelta completa). En su interior, estas boquillas de plástico llevan grabadas unas líneas paralelas a la dirección del flujo de agua que sustituyen a la vaina prolongadora de chorro. La ventaja de estas nuevas boquillas es que reducen el tiempo dedicado al mantenimiento y supervisión de la instalación por parte de los agricultores y evita el riesgo de dañar o perder la vaina prolongadora. Sin embargo, no existen trabajos que evalúen su comportamiento en términos de uniformidad de reparto de agua.

La uniformidad del reparto del agua en riego por aspersión cuantifica la variabilidad espacial de la distribución del agua en una parcela. Varios estudios se han centrado en la definición de parámetros que afectan la uniformidad (Merriam y Keller, 1978; Heermann, 1990; Clemmens y Dedrick, 1994; Burt y col., 1997). La uniformidad del riego depende tanto de los factores de diseño (tipo de aspersor, el uso de una o dos boquillas en el aspersor, diámetro de las boquillas, marco de aspersión en la parcela y la existencia o no de vaina prolongadora de chorros) como de los factores de funcionamiento (tiempo de riego, presión de funcionamiento, tipo de cultivo) y de las condiciones ambientales durante el riego (Keller y Bliesner, 1990; Carrión y col., 2001; Playán y col., 2006; Sánchez y col., 2010). Los sistemas de riego por aspersión requieren un valor mínimo de uniformidad para ser considerados aceptables. Keller y Bliesner (1990) clasifican la uniformidad de riego como "baja" cuando el Coeficiente de Uniformidad de Christiansen (CUC, Christiansen, 1942) es inferior al 84 %.

Las evaluaciones experimentales de la uniformidad del riego requieren un importante esfuerzo de trabajo de campo, lo que genera un alto coste económico debido al elevado número de combinaciones posibles a evaluar al variar las variables involucradas. Los modelos matemáticos son una buena herramienta que facilita el análisis de las variables implicadas. Muchos de los modelos matemáticos que evalúan la distribución del agua en riego por aspersión se basan en la teoría balística (Okamura, 1968; Okamura y Nakanishi, 1969; Fukui y col., 1980, Montero y col., 2001, Playán y col., 2006). Mediante esta teoría balística se calcula la trayectoria y el punto de contacto con el suelo o con la superficie vegetal de las gotas, caracterizadas por su diámetro efectivo y su velocidad. Las gotas salen del aspersor con una determinada velocidad y trayectoria y se ven afectadas por una serie de fuerzas vectoriales; la fuerza gravitacional, la resistencia aerodinámica y el viento. La suma vectorial de todas ellas determina el punto de aterrizaje de las gotas. Repitiendo este proceso para cada tamaño de gota, se obtiene la distribución de agua del sistema de riego. Entre los modelos basados en la teoría balística, cabe destacar SIRIAS (Montero y col., 2001) y Ador-Aspersión (Playán y col., 2006), ya que presentan un software de aplicación práctica de fácil manejo. La ventaja de estos modelos es que están calibrados y validados para diferentes materiales de riego, condiciones de funcionamiento y condiciones meteorológicas. Sin embargo, entre los materiales de riego calibrados y validados no aparecen aspersores de impacto de plástico, ni boquillas de plástico. Los emisores de material plástico, debido a su bajo coste, están siendo una alternativa a los aspersores metálicos en las nuevas modernizaciones de riego. También las boquillas de plástico son una alternativa novedosa que aporta ventajas al manejo de los sistemas de riego. Por ello se hace necesario evaluar estos nuevos materiales (en nuestro caso boquillas) siguiendo la metodología que permita su incorporación a los programas de simulación de riego por aspersión en parcela.

El desarrollo de nuevos regadíos y la modernización de los regadíos tradicionales a riegos presurizados han incrementado notablemente el consumo de energía en el sector agrícola. En España, el consumo energético en la agricultura ha alcanzando el 4,5% sobre el total de los consumos de energía a nivel nacional. De este consumo energético, el 70% corresponde a la maquinaría agrícola junto con el consumo de los regadíos (IDAE, 2008). Distintos estudios sobre la gestión de los riegos se están llevando a cabo con el objetivo de obtener la máxima eficiencia en el uso del agua y de la energía. Abadía et al. (2010) presentan la metodología y el análisis de la eficiencia energética en Comunidades de Regantes de las regiones de Castilla-La Mancha, Valencia y Murcia.

Sin embargo, pocos son los trabajos de seguimiento y mejora de la eficiencia energética en los regadíos aragoneses. En esta tesis, se ha efectuado el análisis de la eficiencia energética en la Comunidad de Regantes de Almudevar. La mejora del uso del agua en una Comunidad de Regantes presurizada supone un ahorro de agua y de la energía asociada a su aplicación. La disponibilidad de datos a tiempo real sobre los consumos de agua de riego que ofrecen los sistemas de telecontrol, y la posibilidad de analizar las demandas futuras permite realizar una distribución de las demandas de agua acordes con las contrataciones de potencia, con los periodos tarifarios de la factura eléctrica y con los condicionantes de la red de riego.

El contexto actual de crisis económica ha ralentizado y en la mayoría de los casos paralizado los procesos de modernización de los regadíos. La perspectiva para los próximos años de recortes en la financiación pública hace prever que estos procesos de modernización tardarán en volverse a impulsar. Las comunidades de regantes modernizadas en los últimos años han superado varios de los retos que planteaba el Plan Nacional de Regadío (PNR-2008), sin embargo, ahora se enfrentan a otros nuevos. Estas comunidades tienen que hacer frente a la amortización de las inversiones realizadas en el proceso de modernización, a los elevados costes eléctricos de los bombeos, a los mercados agrarios cambiantes y a las situaciones de incertidumbre en la disponibilidad de agua (sequías y/o poca capacidad de almacenamiento). Para afrontar estos retos hay que explorar y explotar la gran cantidad de información que ponen a nuestra disposición los trabajos de investigación y experimentación ya realizados y las nuevas tecnologías que se utilizan en la gestión del riego en las Comunidades de Regantes modernizadas.

En esta tesis se evalúan las posibilidades que ofrecen los nuevos desarrollos en el campo de la agricultura de regadío. En el capítulo II de esta tesis se analizan las posibilidades que ofrecen los nuevos desarrollos en el campo de los emisores de riego, en este caso las boquillas de plástico para aspersores de impacto de coberturas de riego por aspersión. Estas boquillas tienen la ventaja de que se insertan y se desmontan con mayor facilidad que las boquillas clásicas de latón. En este apartado de la tesis, los resultados obtenidos de las evaluaciones en campo del riego por aspersión usando el aspersor con nuevas boquillas de plástico se compararon con otros modelos convencionales de aspersores bajo una amplia gama de condiciones ambientales y de gestión.

El capítulo III aborda aspectos más agronómicos del riego por aspersión, en concreto las pérdidas netas en coberturas de riego por aspersión, pero que también afectan a la gestión de los riegos. Estas pérdidas netas son una de las variables clave que participan en la toma de decisiones del riego, y por lo tanto afectan a la gestión de los mismos.

Los capítulos IV y V abordan las posibilidades que ofrece la explotación de la información disponible y la que generan a tiempo real las nuevas tecnologías en la gestión del riego de una comunidad de regantes. La caracterización de la variabilidad espacial del territorio (propiedades hidráulicas relacionadas con el riego, la agro-meteorología y los sistemas de riego) pone a nuestra disposición información muy útil para la gestión de los riegos. Por otro lado, la información a tiempo real que generan los telecontroles es otra herramienta útil y necesaria en la gestión eficiente del agua y de la energía asociada al riego.

I.2. OBJETIVOS DE LA TESIS

I.2.1. Objetivos generales

El objetivo principal de esta tesis es la contribución al conocimiento del riego por aspersión, haciendo hincapié en las novedades que se han incorporado en las nuevas modernizaciones de regadíos. El análisis de las ventajas e inconvenientes y de las posibilidades que ofrecen al campo de la agricultura de regadío la incorporación de nuevos emisores de riego y de las nuevas tecnologías en telecomunicaciones como los modernos sistemas de telecontrol son los objetivos principales de esta tesis.

Los problemas y sus soluciones se han estudiado desde diferentes ámbitos de la parcela y de la comunidad de regantes. En el ámbito de la parcela se ha avanzado en el conocimiento de los nuevos materiales que se utilizan para los aspersores de impacto, en concreto de las boquillas (boquillas de plástico fáciles de manejar frente a las boquillas tradicionales construidas en latón). También se ha profundizado en la caracterización de las pérdidas netas en riego por aspersión en coberturas totales enterradas. Se ha estudiado la variabilidad existente en una comunidad de regantes con riego presurizado en cuanto a sus condicionantes físicos (tipos de suelo, velocidad del viento, temperatura del aire, etc.) como de manejo del riego (adecuación de los volúmenes de riego aplicados a las necesidades hídricas de los cultivos, pautas de riego según tipos de cultivo y sistema de riego, etc.). Por último, se aborda la mejora de la gestión de las comunidades de regantes explorando las posibilidades actuales del telecontrol en la gestión del agua y de la energía asociada.

I.2.2. Objetivos específicos

1- **Estudio del efecto del modelo de aspersor con nueva boquilla de plástico sobre la calidad del riego bajo distintas condiciones meteorológicas, de funcionamiento y de tamaño de boquillas principales:**

a) Determinar el patrón de distribución radial de la pluviometría de un aspersor con nueva boquilla de plástico en campo y compararlo con el mismo modelo de aspersor convencional con boquillas de latón.

b) Determinar la influencia de distintos factores técnicos y meteorológicos en la distribución de agua de una cobertura de aspersión en campo usando el mismo tipo de aspersor con la boquilla de plástico.

c) Comparar los parámetros de calidad del riego de una cobertura equipada con el aspersor con nuevas boquillas de plástico con su homologo de latón y otros aspersores de impacto utilizados en el valle medio del Ebro bajo distintas condiciones ambientales y de funcionamiento.

2- Determinar las pérdidas totales en riego por aspersión y los cambios microclimáticos y fisiológicos durante y después del riego por aspersión:

a) Estimar las pérdidas por evaporación y arrastre brutas ($WDEL_g$) que se producen en un sistema de riego estacionario sobre un cultivo de alfalfa.

b) Estudiar el efecto de los cambios microclimáticos que se producen durante y después de los eventos del riego por aspersión en alfalfa sobre la evapotranspiración (ET) de los cultivos y sobre las pérdidas totales

c) Determinar y caracterizar la evapotranspiración antes, durante y después del riego de un cultivo de alfalfa y compararla con la que se produce al mismo tiempo en un cultivo de alfalfa que no se está regando.

d) Estimar las pérdidas por evaporación y arrastre netas ($WDEL_n$).

e) Calcular y modelizar las pérdidas por intercepción netas (IL_n).

f) Calcular las pérdidas totales en riego por aspersión (SEL_n) y proporcionar un modelo de fácil uso para los regantes permitiendo evaluar las pérdidas no beneficiosas en cobertura total de riego por aspersión.

3- Análisis de las pautas de riego en comunidades de regantes telecontroladas: La Comunidad de Regantes de Candasnos (con sistema de telecontrol antiguo) y la Comunidad de Regantes de Almudevar (recién modernizada y con nuevo sistema de telecontrol):

a) Caracterizar la adecuación del riego mediante la evaluación del índice estacional de la calidad de riego (SIPI) (evolución espacio-temporal y interanual).

b) Evaluar las pautas de riego de los diferentes cultivos y sistemas de riego presurizado (cobertura, pívots, maquinas de avance frontal y goteo).

c) Caracterizar la secuencia de riego por aspersión en sectores de riego mediante transductores de presión en parcelas controladas (CR de Candasnos) y mediante los datos del telecontrol a nivel de sectores (CR de Almudevar).

d) Identificar herramientas de control y mejora del uso del agua en Comunidades de Regantes.

e) Evaluar la eficiencia energética asociada al consumo de agua de riego (en la Comunidad de Regantes de Almudevar) mediante la explotación de los datos a tiempo real que proporciona el sistema de telecontrol de riego y proponer una metodología que permita la optimización hídrica y energética.

La importancia social y económica del regadío en el territorio español y la necesidad constante de mejora debido a los nuevos retos a los que se enfrenta la agricultura de regadío justifican la realización de la presente Tesis Doctoral, titulada: "***Gestión avanzada del riego por aspersión en parcela: Aplicación en el valle medio del Ebro***". Los Proyectos de Investigación (AGL2007-66716-C03-01/02 y AGL2010-21681-C03-01/03) sobre la mejora de la eficiencia en el uso del agua y de energía en los sistemas de riego presurizado, realizados por el grupo de investigación "Riego, Agronomía y Medioambiente" del Centro de Investigación y Tecnología Agroalimentaria de Aragón (CITA-DGA) y la Estación Experimental de Aula Dei (EEAD-CSIC) han financiado estos trabajos de investigación.

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CHAPTER II: PERFORMANCE OF NEW AGRICULTURAL IMPACT SPRINKLER WITH PLASTIC NOZZLES

PERFORMANCE OF NEW AGRICULTURAL IMPACT SPRINKLER WITH PLASTIC NOZZLES

RESUMEN

La mayoría de los catálogos comerciales de las empresas proveedoras de material de riego por aspersión, no ofrecen información sobre la distribución radial de la distribución del agua de los aspersores (Curva radial, Rad) y presentan solamente datos de la pluviometría teórica a diferentes marcos de aspersión, la descarga y el radio mojado a distintos valores de presión de funcionamiento. En este estudio se evaluó la curva de distribución radial de un nuevo aspersor de impacto con boquillas de plástico "RC130-BY" (Riegos Costa, Lleida, Spain), con diámetros de la boquilla principal de 4,0; 4,5 y 5,0 mm y de 2.5 mm de diámetro en la boquilla auxiliar trabajando a presiones de 200, 300 y 400 kPa. Las curvas radiales (Rad) de este aspersor se obtuvieron al aire libre en condiciones de viento en calma (U ≤1 m s^{-1}). Las curvas radiales resultantes se compararon con las de otros modelos de aspersores de impacto utilizados en el valle medio del Ebro como el mismo modelo de aspersor con boquillas de bronce (RC130-L) y el aspersor VYR-35 (Vyrsa Riegos, Briviesca, Burgos, España). Esta comparación mostró que el modelo de aspersor tiene un efecto importante sobre la distribución del agua de riego y, aunque se den las mismas condiciones técnicas (mismo diámetro de la boquilla y presión de funcionamiento y condiciones similares de viento), la distribución radial varía de un aspersor a otro. Esta variabilidad se mostró especialmente en los primeros 2.5 a 6 metros alrededor del aspersor. También se evaluó este aspersor de impacto en cobertura total enterrada en un marco de aspersión cuadrado de 18 m x 18 m para determinar el coeficiente de uniformidad de Christiansen (CUC) así como las perdidas por evaporación y arrastre (WDEL) para diferentes combinaciones de diámetros de la boquilla, presión de funcionamiento y distintas condiciones de viento. Estos indicadores de calidad de riego obtenidos con el aspersor RC130-BY se compararon con los obtenidos con el modelo de simulación "Ador-Aspersión" para el aspersor con boquillas de bronce (RC130-L). Se realizaron veintiséis ensayos de evaluación de aspersor aislado con viento en calma para determinar la curva radial de pluviometría de este modelo de aspersor para distintas combinaciones de diámetro de boquilla principal (D) y presión de trabajo (p). Las curvas resultantes se compararon con las de otros modelos de aspersor. También se evaluaron cincuenta ensayos correspondientes a seis combinaciones de D y p, bajo una amplia gama de condiciones meteorológicas de una cobertura total enterrada para evaluar el CUC y las WDEL. Finalmente los resultados experimentales de CUC y WDEL de las evaluaciones efectuadas en la cobertura equipada con el aspersor estudiado (RC130-BY) se compararon con los obtenidos con el modelo de simulación "Ador-Aspersión" para el aspersor con boquillas de bronce (RC130-L) bajo las mismas condiciones de funcionamiento. Los resultados de este análisis mostraron que el tipo de aspersor tiene una influencia importante en la uniformidad del riego por aspersión. Los resultados del trabajo muestran que este tipo de herramientas y análisis permiten decidir las combinaciones más convenientes del modelo de aspersor, diámetro de boquillas y presión de trabajo a fin de optimizar la uniformidad y la eficiencia del riego por aspersión.

PALABRAS CLAVE:
Aspersor de impacto, boquilla de plástico, distribución radial, uniformidad, pérdidas por evaporación y arrastre

ABSTRACT

Most sprinkler manufacturer' catalogues do not specify technical information about the radial profile of water distribution (Radial curve, Rad) of the sprinklers and present only information of the theoretical precipitation rate at different sprinkler spacings and about the discharge and wetted radius at different operating pressure values. In this study the radial curve distribution (Rad) of a new agricultural sprinkler with plastic nozzles "RC130-BY"(Riegos Costa, Lleida , Spain), equipped with nozzles 4.0, 4.5 and 5.0 mm of inside diameter in the main nozzle and 2.5 mm in the auxiliary nozzle, working under operating pressures of 200, 300 and 400 kPa were obtained. The radial curves (Rad) of this type of sprinkler were obtained under calm wind (U≤ 1 m s^{-1}) in open air conditions. Also the water application performance parameters of a solid set equipped with this agricultural impact sprinkler with plastic nozzles was analyzed. The resulting radial curves were compared with those of other agricultural impact sprinkler with brass nozzle widely used in the middle Ebro River Valley such as the same model RC130-L and the VYR-35 (Vyrsa Riegos, Briviesca, Burgos, Spain). This comparison showed that the sprinkler model has an important effect on the irrigated water distribution and although under similar operational conditions (same nozzle diameter and operating pressure and similar wind conditions), the radial distribution varies from one to other agricultural impact sprinkler. This variability was shown especially in the first 2.5 to 6 meters around the sprinkler. Also a sprinkler solid set at a square spacing 18 m X 18 m equipped with the same type of sprinkler was evaluated for uniformity and wind drift and evaporation losses for different combination of nozzle diameters and operating pressures under different wind conditions. The performance of this impact sprinkler with the plastic nozzles was compared with the same type of sprinklers with brass nozzles which are normally used. Twenty-six evaluation tests with an isolated sprinkler corresponding to different combinations of three working pressure (p) and three nozzle diameters (D) of the main nozzle were performed to evaluate the radial curves (Rad). Also Fifty tests corresponding to six combinations of D and p were performed under a wide range of meteorological conditions in a rectangular solid-set system at 18 m X 18 m sprinkler spacing to evaluate the Uniformity Coefficient of Christiansen's (CUC) and the Wind Drift and Evaporation Losses (WDEL). Finally the experimental CUC and WDEL of the solid set with the "RC130-BY"sprinkler were compared with the simulated values obtained with the simulation model "Ador-Sprinkle" for the same sprinkler model with brass nozzles (RC130-L) under the same operational conditions. The results of this analysis showed that the type of sprinkler has an important influence on the sprinkler irrigation uniformity and that this type of analysis tools, may serve as a decision making to choose the most suitable combinations of sprinkler model, nozzle diameter and working pressure to optimize the uniformity and efficiency of sprinkler irrigation.

KEY WORDS:
Impact sprinkler, plastic nozzle, radial distribution, uniformity, wind drift and evaporation losses

ABBREVIATION

A	= Section of the nozzle
AMRE	= Magnitude of the relative error
C_D	= Discharge coefficient
CUC	= Christiansen coefficient of uniformity
D	= Nozzle diameter
d	= Auxiliary nozzle diameter
E	= Coefficient of efficiency
g	= Gravity acceleration
ID	= Irrigation depth
ID_{CC}	= Irrigation depth collected in pluviometers
N	= Number of pluviometers
h_m	= Mean water depth collected
h_i	= Water depth collected in pluviometer i
IS	= Similarity index
IT	= Irrigation time
k	= Constant
MSE	= Mean square error
p	= Working pressure
Pred [0.25]	= The level of prediction to 25 %
Q	= Water discharge
Rad	= Sprinkler radial curve
RH	= Air relative humidity
RMSE	= Root mean square error
R18x18	= Rectangular spacing of 18 m x 18 m
R^2	= Coefficient of determination

S	= Area of sprinkler spacing
SD	= Standard deviation.
SV	= Straightening vane
T	= Air temperature
t	= Time
T18x18	= Triangular spacing of 18 m x 18 m
WDEL	= Wind drift and evaporation losses
U	= Wind speed
WDEL	= Wind drift and evaporation losses
WD	= Wind direction
α	= Statistical significance
3-D	= Three dimensional

II.1. INTRODUCTION

Solid-set sprinkler irrigation has been commonly used around the world because it improves water application efficiency, increases crop production, and decreases environmental impact of irrigation. The uniformity of water distribution is a very important factor in the design and management of these sprinkler irrigation systems. Uniformity of water distribution through irrigation systems plays an important role in optimizing water usage and directly affects efficiency and production (Carrión et al., 2001). Generally, uniformity of distribution is the main method used to determine whether an irrigation system is acceptable or not (Brennan, 2008). The knowledge of the water discharge along the wetted radius of an impact sprinkler is crucial to characterize the water distribution and uniformity of a sprinkler system. This relationship between the discharge and distance to the sprinkler is known as the radial curve of the sprinkler (Rad).

A representative sprinkler radial curve must be obtained under calm conditions to avoid the strong effect of wind in the sprinkler water distribution (Tarjuelo et al., 1999a). Therefore, ideally the tests to obtain these curves should be obtained in indoor laboratories to ensure calm conditions. However these facilities often are not available and tests have to be made under open-air conditions in very calm wind periods. The absence of wind is necessary in order to obtain a reliable radial curve. Experiments made by Sánchez et al. (2011) showed that even under very low winds with a dominant direction, important changes were observed in the water collected in four radii of pluviometers located in north, south, east and west directions around an isolated sprinkler. They found a threshold value of 0.6 m s^{-1} for the reliable determination of Rad in open air conditions. The evaluation of sprinkler irrigation performance is usually accomplished by one or more measures of water application uniformity and or water application efficiency indices.

The uniformity of a solid-set system under calm conditions can be assessed through the overlap of the individual water distribution of sprinklers at the selected sprinkler spacing (Tarjuelo et al. 1999a). Theoretically the water distribution derived from the Rad has a circular shape. However under field conditions usually the sprinkler distributions are deformed due to wind speed and direction. The determination of sprinkler uniformity at the farm level requires the evaluation of the sprinkler system under field operation conditions or the use of mathematical simulation models that take into account the modification of the water distribution of the sprinklers due to the design and management parameters which affect the performance of sprinkler irrigation. These models facilitate the evaluation of sprinkler irrigation under a wide range of management and environmental conditions with low experimental effort.

The sprinkler irrigation uniformity depends on design and operational factors. The most important design factors are the sprinkler type, the use of one or two nozzles, the nozzle diameters and the sprinkler spacing. The operational factors include the working pressure, the time of irrigation and the environmental conditions during irrigation, mainly wind speed (Keller and Bliesner, 1990; Carrión et al., 2001; Playán et al., 2006). Sánchez et al., 2010a y 2010b compared irrigation uniformity and wind drift and evaporation losses (WDEL) in sprinkler irrigated maize and alfalfa and found that the sprinkler performance parameters were affected also by the height of the pluviometers where the water application was measured. They concluded that the height and type of the crop canopy had an important effect in the uniformity and WDEL in sprinkler solid sets.

Wind speed is the meteorological variable more directly related with the irrigation performance through its effects on the Christiansen's uniformity coefficient (CUC) and on the WDEL (Playán et al., 2005). Faci and Bercero (1991) found that sprinkler CUC of solid sets decrease when wind speed (U) was greater than 2 m s^{-1}. Dechmi et al. (2003) and Playán et al. (2006) found that CUC of lateral move machines was less affected by wind speed than solid sets.

Usually solid sets in the Ebro River Basin use metallic impact sprinklers with brass nozzles screwed in the body of the sprinkler. When these nozzles are plugged it is necessary to use a tool to unscrew and clean them. Many times this task is complicated since the sprinklers often are installed at 2.3 m above the ground level and also the jet straightening vane (SV) located inside the main nozzle can be lost in the unplugging process. In order to avoid these problems some sprinkler commercial firms have developed sprinkler with plastic nozzles that can be easily removed or inserted in the sprinklers by hand with a simple turn of the nozzle of 90 º (¼ of a complete turn). These plastic nozzles have engraved some parallel lines in the inside of the nozzle in the direction of the water flow that avoid the use of the jet straightening vane (SV). The SV equally decreases distortion by wind making the jet more compact and achieving a farther throw. It has already been shown that when using the SV for a wind speed higher than 2 m s^{-1}, obtained CUC values are higher (Tarjuelo et al., 1995).

Farmers using this type of sprinkler with plastic nozzles have indicated an important advantage since they can easily remove the nozzle by hand, clean it and replace it in the sprinkler body just with a simple turn of the nozzle once it is inserted in the body of the sprinkler. The farmers have reported that they perform this simple operation while the sprinkler system is operating.

This study includes the determination of the radial curve (Rad) of an agricultural impact sprinkler with plastic nozzles operating at different working pressures and with different diameter of the main nozzle. It also analyzes the irrigation uniformity of a solid set equipped with this type of sprinkler. Results of the experimental radial curves and solid set evaluations were compared with results obtained with other common impact sprinklers and in the same experimental conditions but with the traditional brass nozzles.

II.2. MATERIAL AND METHODS

Irrigation evaluations were conducted at the experimental farm of the Agrifood Research and Technology Centre of Aragón in Zaragoza, Spain (41º43′ N, 0º48′ W, 225 m altitude) during the years 2009 and 2010. Two sets of experiments were performed. The first set was performed with an isolated sprinkler located above bare soil in a plot of the experimental farm. The second set of experiments was performed in a solid set at a rectangular spacing of 18 m x 18 m (R18x18) in other plot of the same experimental farm. The experiments were made taking into consideration the recommendations of Merriam and Keller (1978) and the relevant International Standards: ASAE S330.1 (Anonymous, 1987), ISO 7749/1 (Anonymous, 1995) and ISO 7749/2 (Anonymous, 1990).

The sprinkler used in all experiment tests was the impact sprinkler model RC130-BY (Riegos Costa, Lleida, Spain). The body of the sprinkler is made of brass provided with two outlets for the insertion of the plastic main and auxiliary nozzles with an easy coupling. The mention of trade names of commercial products in this chapter is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the CITA-DGA or by the CSIC.

II.2.1. Isolated sprinkler tests

An isolated sprinkler was installed in a riser pipe at 2 m above the ground level (a.g.l). The irrigation depth (ID) emitted by the sprinkler was collected in pluviometers located along four perpendicular radii oriented according to the four cardinal points and at distances from the sprinkler ranging from 0.3 to 16.3 m and separated at 0.5 m (Figure II.1). Additional pluviometers were installed at 0.15 m and 0.3 m from the sprinkler in each radius to determine precisely the ID in the area adjacent to the sprinkler. A total number of 34 catch cans were installed in each radius at 0.4 m above the ground level. The radii faced north (N), west (W), south (S) and east (E) directions, respectively (Figure II.1). The pluviometer was 40 cm high and had a trunk conic shape with a circular opening of 16 cm. The precision of the pluviometer was 1 mm of precipitation. Experimental plot was surrounded by windbreaks trees to palliate the effect of the wind as shown in Figure II.1. In each radius, the first two pluviometers were installed at 0.15 m from the sprinkler to a better understanding of the water distribution near the sprinkler. The other 32 pluviometers were installed at 0.5 m distance (Figure II.1).

Three diameters (D) of the main nozzle were tested in the isolated tests: 4, 4.5 and 5 mm. The sprinkler included in all tests a plastic auxiliary nozzle, 2.5 mm in diameter. The sprinkler was operated at around three ranges of working pressure (p) (200, 300 and 400 KPa). Since absolute calm was not possible, tests were performed under calm conditions or very low wind conditions ($U \leq 1$ m s^{-1}). The mean duration of the tests was two hours. Twenty six tests with different combinations of D and p were performed but only nine tests with lower wind speed were selected to determine the Rad (Table II.1).

The working pressure in the isolated sprinkler installation was controlled with manual valves and a manometer installed in the head control of the experiment (Figure II.1). The working pressure at the sprinkler was measured with a pressure transducer connected to a data logger (E120, Dixon, Addison, IL, USA) installed in the pipe riser at 20 cm of the sprinkler nozzles. The water discharge of the isolated sprinkler was measured with a volumetric water meter installed in the head control of the experiment (Figure II.1).

The wind speed (U) and direction (WD), the temperature (T) and relative humidity (RH) of the air were monitored by an automatic meteorological station located in an adjacent plot to the experimental site during the tests. The average records of the meteorological variables were collected every five minutes by a data-logger model CR10X (Campbell Scientific Ltd, UK). In each isolated test, the depth of water collected at each distance from the sprinkler in each radius was averaged and the standard deviation in the four radii was calculated. The average Rad from each combination of D and p was used to calculate the theoretical CUC under calm conditions in a rectangular sprinkler spacing of 18 m by 18 m (R18x18) equal to the solid-set experiment spacing.

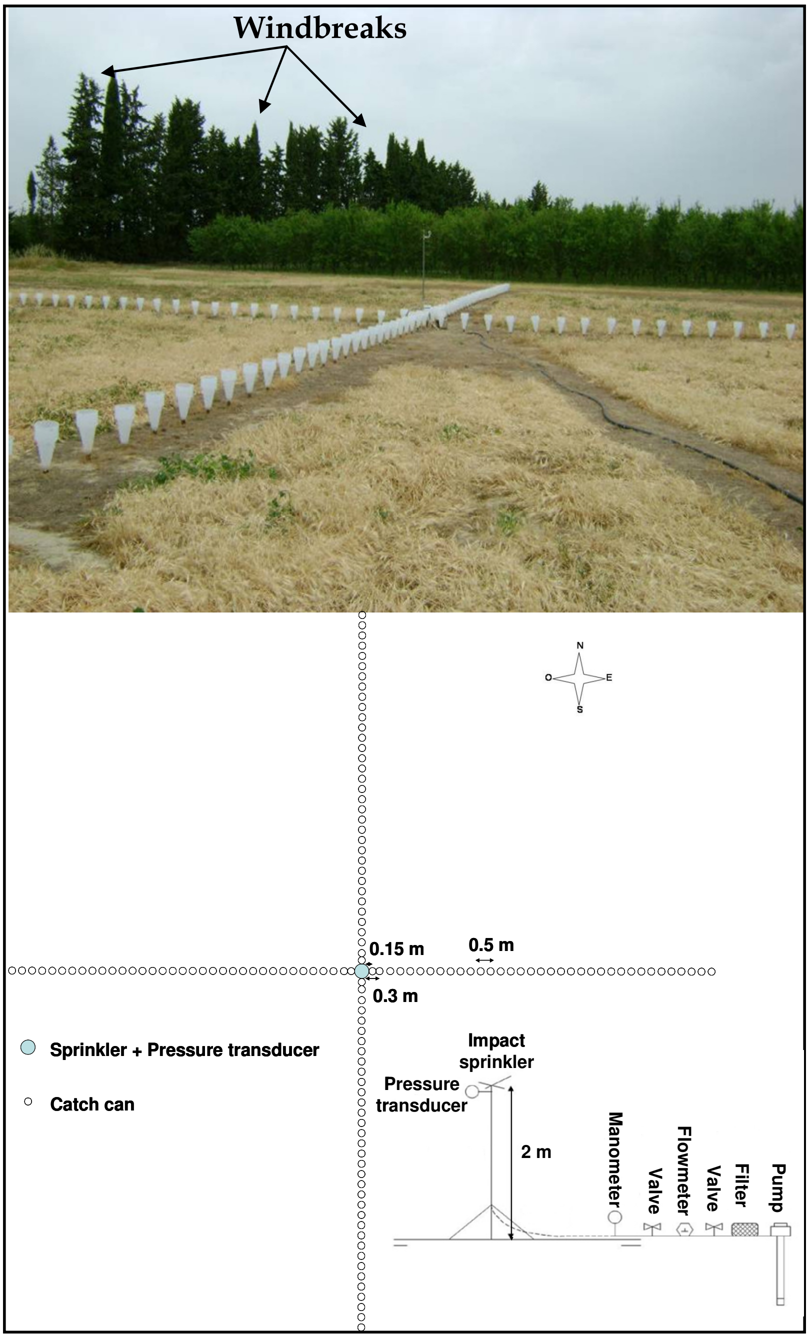

Figure II. 1. *On-farm arrangement of the pluviometers (upper picture) and facilities (lower picture) for the isolated test to determine the radial curves for the RC130-BY sprinkler*

For each isolated sprinkler test, the water distributions in each radius were compared. The tests in which the differences between the radii were the smallest were used to characterize the Rad. For each test, the average standard deviation of the collected irrigation depth along the four radii (SD, mmh^{-1}) was calculated.

Three sprinkler models were compared: the RC130-BY evaluated in this research, the RC130-L evaluated by Playán et al. (2006) and the VYR-35 evaluated by Zapata et al. (2007).

All are widely used in the solid set systems in the Ebro Valley (Spain). A Rad comparison was made for calm conditions for these three sprinklers.

II.2.2. Solid set experiment

The solid set tests were performed in a plot of the same experimental farm equipped with 16 sprinklers RC130-BY with plastic nozzles at a regular spacing of 18 m X 18 m. Irrigation performance was evaluated using the collected irrigation depth in a network of 25 pluviometers installed at 3.6 m x 3.6 m in the area between the four sprinklers located in the center of the experimental field (Figure II.2). Each catch can represent an area of 13 m^2. Rows of plastic platforms were installed in the experimental area in order to facilitate the access to the pluviometers. The uniformity coefficient of Christiansen (CUC) (Christiansen, 1942) and the wind drift and evaporation losses (WDEL) were assessed from the ID collected in the pluviometers. The same type of pluviometer as the one used in the isolated sprinkler experiments was used.

The CUC in each evaluation was calculated using the following equation (Christiansen, 1942):

$$CUC = 100 \times \left(1 - \frac{\sum_{i=1}^{i=25} \left| h_m - h_i \right|}{n \times h_m} \right) \quad \text{(II.1)}$$

Where:

n: Number of pluviometers.

h_m: Mean water depth collected.

h_i: Water depth collected in pluviometer i.

$\sum_{i=1}^{i=25} \left| h_m - h_i \right|$: Sum of the absolute values of the individual deviation from the mean of the water depth collected.

The water depth emitted by the sprinkler (ID, L m^{-2}) was calculated in each test using the following equation:

$$ID = \frac{Q \ t}{S} \quad \text{(II.2)}$$

Where:

Q: Water discharge (L s^{-1}) calculated with equation (II.3)

t: Duration of the test in seconds

S: Area of sprinkler spacing (m^2), in our case is 18x18=324 m^2

The discharge of the sprinklers (Q, L s^{-1}) was estimated using the Torricelli's theorem and the Orifice Equation, (Norman et al. 1990) that is expressed as:

$$Q = C_D \times A \times (2gp)^k \tag{II.3}$$

Where:

C_D: Discharge coefficient (calculated experimentally for each combination of D and p)

A: Section of the nozzles orifices (mm^2)

g: Gravity acceleration (m s^{-2})

p: Pressure in nozzle (kPa).

k: Constant

Concerning equation (II.3), several studies applied to agricultural sprinklers interpreted that C_D is essentially independent of p for a given nozzle and that *k* is constant and equal to 0.5 (Li, 1996; Li and Kawano, 1998; Tarjuelo et al., 1999a). In the present work it was also assumed that *k* was equal to 0.5.

The discharge coefficient (C_D) of equation (II.3) was assessed by the calculation of the sprinkler discharge (Q, L s^{-1}) as the difference between the flow meter reading before and after each isolated sprinkler test for each nozzle diameter (D).

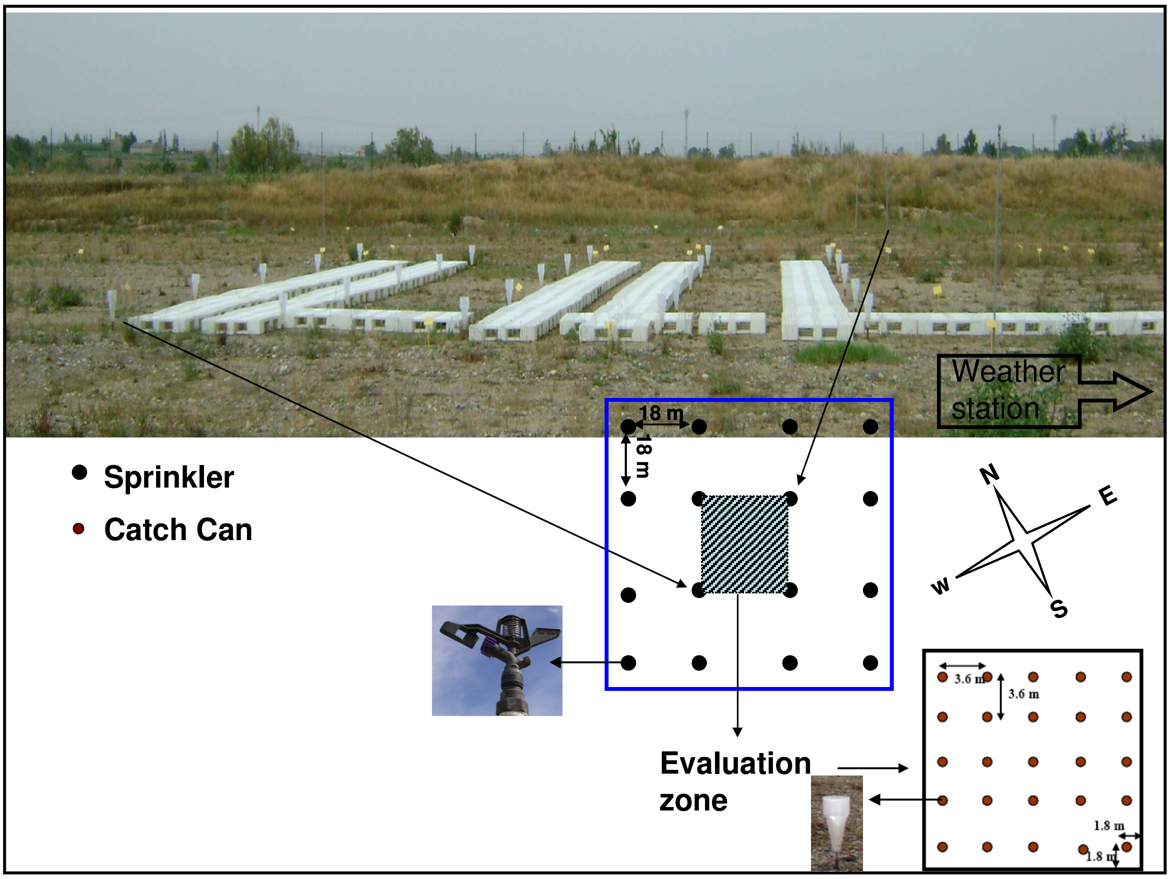

***Figure II. 2**. Arrangement of the solid set sprinkler experimental plot, facilities and network of pluviometers in the experimental plot for the solid-set experiment.*

The WDEL during each test was estimated as the percentage of the water depth emitted by the sprinklers (*ID*) that was not collected in the pluviometers (Dechmi et al., 2003; Playán et al., 2005; Sanchez et al., 2010a):

$$WDEL = \frac{ID - ID_{CC}}{ID} \times 100 \qquad \text{(II.4)}$$

Where:

ID_{CC}: Average water depth collected in the pluviometers.

ID: Average water depth emitted by the sprinkler.

A meteorological station similar to the one used during the isolated-sprinkler test was located close to the experimental plot during the solid-set experiments. The experiments were performed under a wide range of meteorological conditions in an attempt to characterize the CUC and the WDEL resulting from different combinations of D and p. A multiple regression analysis was performed to investigate the variation of the CUC and of the WDEL with irrigation duration, nozzle diameter, operating pressure, wind speed, air temperature and relative humidity. The suitable predictive equations of CUC and WDEL as a function of technical and meteorological variables were selected through a backward stepwise procedure accounting for their statistical indicators used to monitor and compare the selected equations (Dolado, 1990). The adjusted coefficient of determination (adjusted R^2), the mean square error (MSE), the coefficient of efficiency (E) defined by Wilcox et al. (1990), the similarity index (IS) (Willmott, 1981) and the root mean square error (RMSE) were analyzed. Two additional statistics parameters were introduced to evaluate the predictive capability of the equations: the average magnitude of the relative error (AMRE, %) and the prediction level 25 (Pred [0.25]) (Dolado, 1999). The Pred [0.25] is the percentage of the estimated values differing from the measured value by less than 25% (Dolado, 1990 and Playán et al., 2005).

The CUC and the WDEL of a solid set with the same spacing as the one used in the experiment (18 m x 18 m) was simulated for the same sprinkler model but with the brass nozzles and under the same operating and meteorological conditions using the ballistic model Ador-sprinkler (Dechmi et al. 2004 a; b and Playán et al., 2006). A comparison between the RC130-BY and the RC130-L irrigation performances (CUC and WDEL) was made in calm and windy conditions for a solid set configuration of R 18X18. A comparison between the CUC of the RC130-BY and the RC130-L was performed with experimental data made by Playán et al. (2006) for the RC130-L with a nozzle diameters of 4.4+2.4 mm, p ranging between 328 and 350 kPa, U from 0.6 to 4.4 m s^{-1} and arranged for a solid set at a triangular spacing 18 m by 18 m (T 18X18).

Table II. 1. *Operational and meteorological conditions of the 26 tests performed with the isolated sprinkler model RC130-BY: diameter of the main and auxiliary nozzles (D + d, mm), operating pressure (p, kPa), irrigation time (IT, h), sprinkler discharge (Q, L h^{-1}), average air temperature (T, ◦C), average air relative humidity (RH, %), average standard deviation of the irrigation depth between the four radii (SD ID, mm h^{-1}), average wind speed (U, m s^{-1}), average wind direction (WD) and dominant wind direction frequency (Fr, %).*

D+d (mm)	p (kPa)	IT (h)	Q (L h^{-1})	T (°C)	HR (%)	SD ID (mm h^{-1})	WIND		
							U (m s^{-1})	WD	Fr. (%)
4+2.5	200	2.0	1138	7.2	90	0.40	1.1	NW	50
	194	2.0	1140	17.7	47	0.21	0.7	ENE	50
	196	**3.5**	**1140**	**27.2**	**46**	**0.11**	**1.0**	**SE**	**14**
	277	2.0	1377	21.7	44	0.10	0.7	SW	75
	285	**2.0**	**1400**	**9.2**	**71**	**0.18**	**0.8**	**S**	**25**
	271	1.9	1346	28.5	45	0.18	0.8	ENE/NE+	34
	386	2.0	1567	9.2	64	0.39	1.1	N	25
	386	2.0	1570	12	63	0.56	0.3	SW/SSW+	80
	388	2.0	1580	14	67	0.36	0.6	SSE	75
	390	2.0	1593	14.6	53	0.80	1.2	S	33
	360	3.0	1544	22.4	47	0.48	1.2	SW/SSW+	50
	400	**2.0**	**1678**	**24.3**	**48**	**0.16**	**0.9**	**NW**	**22**
4.5+2.5	173	1.9	1312	13.5	52	0.29	0.8	WNW	75
	175	2.0	1298	6.7	89	0.13	0.3	SE	50
	188	2.0	1411	24.3	45	0.24	0.6	N	20
	183	2.1	1390	26.8	52	0.29	1.0	W	19
	198	**1.9**	**1448**	**19.3**	**48**	**0.14**	**0.9**	**NNE**	**29**
	290	2.0	1598	10.2	80	0.33	0.3	WNW	75
	293	2.0	1595	5.9	78	0.28	0.4	N	75
	290	**2.0**	**1677**	**27.4**	**48**	**0.13**	**0.8**	**NE/NNE**	**24**
	369	2.0	1847	6.5	74	0.41	0.9	NO	25
	370	**2.0**	**1850**	**14.1**	**51**	**0.16**	**0.6**	**SE**	**25**
	372	2.1	1924	23.3	53	0.47	1.3	NW/WNW+	60
5+2.5	**214**	**2.0**	**1930**	**4.2**	**100**	**0.19**	**0.6**	**NW**	**33**
	292	**2.1**	**2064**	**7.1**	**99**	**0.17**	**1.0**	**SSO**	**33**
	385	2.1	2372	11.3	75	0.30	1.5	N	77

The bold numbers corresponds to tests considered suitable for the characterization of the Rad and used in this chapter
+ Two wind directions were dominants

II. 3. RESULTS AND DISCUSSION

II.3.1 Isolated sprinkler tests

Figure II.3 presents the relationship between the sprinkler discharge and the operating pressure for the individual tests performed with the isolated sprinkler RC130-BY equipped with an auxiliary nozzle of 2.5 mm and main nozzle of 4, 4.5 and 5 mm inside diameter. In the three cases the sprinkler discharge increased as the operating pressure (p) increases and the power regression equations were highly significant with coefficient of determination (R^2) values higher than 0.945.

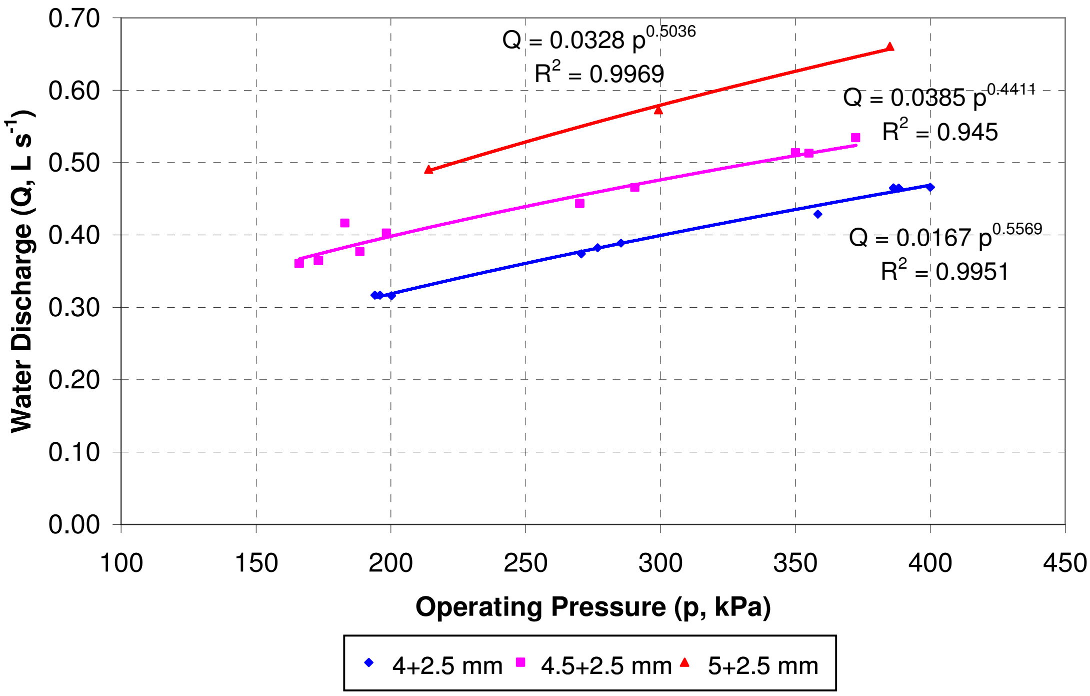

***Figure II.** 3.Relation between the water discharge of the sprinkler RC130-BY (Q, L s-1) assessed by the flow meter measurements and the operation pressure (p, kPa) for all isolated tests. Power regression equations corresponding to the three nozzle diameters (D= 4.0+2.5, 4.5+2.5 and 5.0+2.5 mm) are included.*

The parameter C_D of equation (II.3) was assessed by a nonlinear regression analysis of the evaluated values of Q fitted to a power curve. The calculated values of C_D for the nozzle diameters (D) of 4.0+2.5, 4.5+2.5 and 5.0+2.5 mm, were 0.940, 0.953 and 0.971, respectively. A very slight increase of the C_D was found as the D increases.

A summary of the results of all tests performed in the isolated-sprinkler experiment to assess the Rad of the ID (mm h^{-1}) for different combinations of D and p are presented in Table II.1. The average irrigation time of the isolated sprinkler tests was 2.1 h and ranged between 1.9 and 3.5 h. Most of the tests were conducted under calm conditions but in some of them the wind speed increased during the test and therefore the water distribution changed increasing the standard deviation of the ID (mm h^{-1}) measurements of the four radii of pluviometers. In the experimental open air conditions resulted almost impossible to perform the test under total calm conditions. Wind always blows even imperceptibly. The average wind velocity during all isolated sprinkler tests was 0.8 m s^{-1} and ranged between 0.3 and 1.5 m s^{-1}.

The Rad for each test was calculated as the average of the water distribution in the four radii. This is based on the idea that the distribution of the water applied must be equal in the four radii under calm conditions. However, the distribution of water collected noticeably differed between radii in many tests, both in the shape and in the total volume of water collected (Figure II.4). This effect was clearly observed in the standard deviation along the radius of the different radial curves presented in Figure II.4 for different combinations of main nozzle diameter and operating pressure.

Table II.1 presents the average values of the standard deviation of ID (mm h^{-1}) along the four radii. This value summarizes the similarity of the water distribution obtained in the four radii of pluviometers in each isolated sprinkler test. The average value for all tests was 0.29 mm h^{-1} and ranged from 0.1 to 0.8 mm h^{-1} for all tests. However, the wind speed is not the only variable affecting the radial distribution, the wind direction is also a variable that affects the Rad. Sánchez et al. (2011) found that prevailing winds, even very low in velocity, drifted an important volume of water, for this reason, it is necessary to evaluate the predominant wind direction before selecting a suitable Rad.

Special attention was also paid to the differences at the longest distances from the sprinkler; they imply greater differences in the volume collected along each radius because the area watered by the sprinkler increases with the distance. The dominant wind direction frequency for all isolated tests was presented in table II.1. For the selected Rad, the dominant wind direction frequency has not exceeded the 33% of the experimental time and therefore, the irrigation water distributions was not clearly displaced in one direction and for the four radii the collected ID were similar.

Figure II.4 presents the ID collected in the four radii for nine combinations of main nozzle diameter (D) and operating pressure (p). In all tests of Figure II.4, the distribution of water depth collected in the four radii were very similar, except of the test with the combination D=5.0+2.5 mm and p=400kPa. In this case the ID distribution differs for the four radii in the

7 m distance from the sprinkler because the wind speed (U) was the highest of all tests with an average value of 1.5 m s^{-1}; therefore this test is not considered appropriate to characterize the Rad under this combination of D and p.

After analyzing all the experiments, we selected those in which the ID distribution in the our radii was uniform, and the Rad was obtained for each combination of main nozzle diameter and pressure. For the nine experiments presented in Figure II.4, we considered eight suitable for the Rad characterization.

From the Rad we generated a three dimensional (3-D) cone of revolution corresponding to the ID distribution of an individual sprinkler assuming completely calm conditions (Figure II.5). Figure II.5 was prepared using the SURFER 8.0 program that draws a 3-D cone of revolution, for eight combinations of D and p presented in Figure II.4. In the 3-D figures of water distribution with the nozzle diameters of 4.0+2.5 and 4.5+2.5 mm and for all operation pressure, a decrease in the ID is clearly observed in the vicinity of the sprinkler. However for the combinations of nozzle diameters 5.0+2.5 mm and p=200, 300 kPa, the ID close to the sprinkler was high. For the three main nozzle diameters an increase of the operating pressure increased ID in the vicinity of the sprinkler in an area of around 4 m and this effect was more pronounced for larger nozzle diameters.

Changes in main nozzle or in the operating pressure had more influence on the amount of water delivered by the sprinkler than on the shape of the Rad. Tarjuelo y col. (1999a) reported that the shape of the Rad is mainly determined by the sprinkler model and its internal design, the discharge angle and by the jet break-up of the sprinkler.

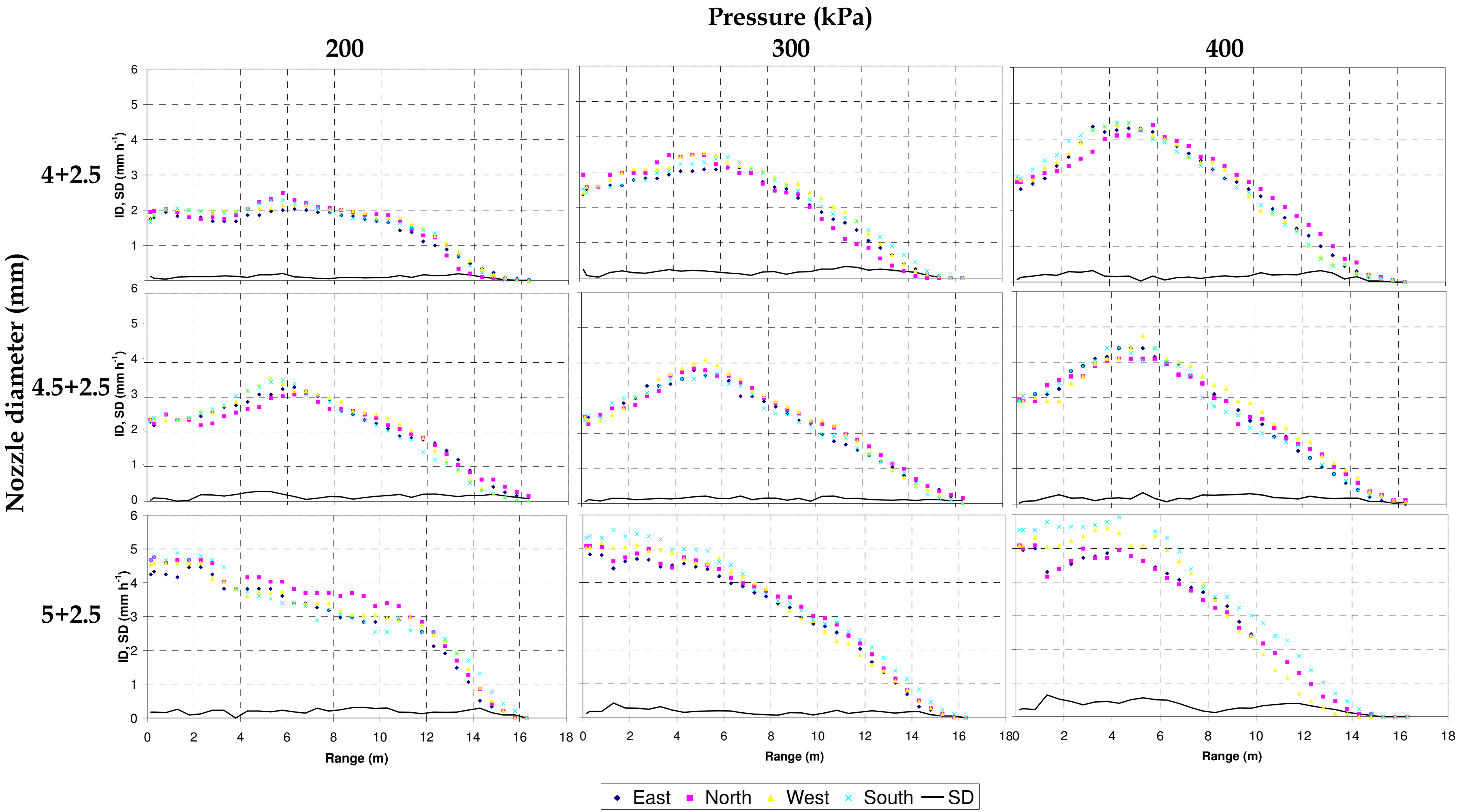

Figure II. 4. *The irrigation depth ID (mm h-1) as a function of the distance from the sprinkler (in m) for the RC130-BYsprinkler model operating with different main nozzle diameter and pressure. The points indicate the observed values of the ID collected along the four radii of pluviometers. Black line corresponds to the standard deviation values of the ID (SD ID) along the wetted radius of the sprinkler.*

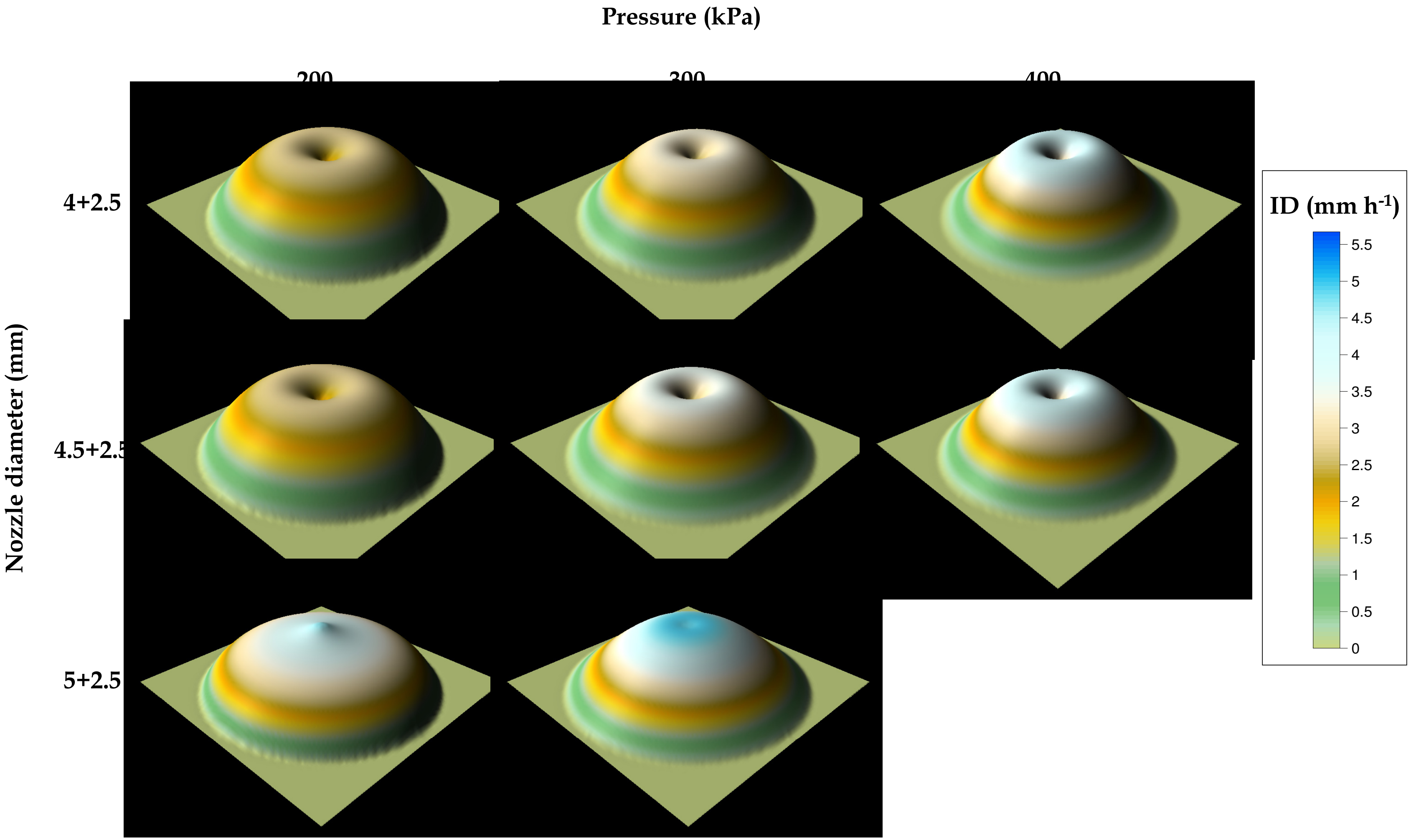

Figure II. 5. *Three dimensional representation of the ID of the RC130-BY sprinkler for the eight selected Rad with different main nozzle diameter and operating pressure. The irrigation depth (ID, mm h^{-1}) are represented with a range of colors from green (minimum ID values) to blue (maximum ID values)*

II. 3.2. Comparison of radial curves of isolated sprinklers with plastic and brass nozzles

The radial patterns obtained with the sprinkler model RC130-BY in the present work, were compared with the existing radial curves for sprinkler models RC130-L and VYR-35 obtained in previous works in the same experimental farm by researchers of the CITA and EEAD. Comparisons were made by the method of paired samples, using the data of the tests of the different sprinkler models performed for the same nozzle diameter (D) and operating pressure (p).

Figure II.6 shows the average Rad for the three sprinkler models and combinations of D and p (notice some differences in the D and p between models). All the models included SV in the main nozzle and an auxiliary nozzle of 2.5 mm inside diameter for the RC130-BY and 2.4 mm for the RC130-L and VYR-35. The Rad noticeably differed between models (Figure II.6). Since the sprinklers presented similar configuration of nozzles (except of the 4.5 and the 5.0 mm diameters of the plastic nozzles of the RC130-BY model, that were slightly close to the 4.4 and 4.8 mm diameters used for the two other sprinkler models). The different shape of the Rad found between the sprinkler models was mainly due to the inner design of the sprinklers and nozzles. As shown in figure II.6, the RC130-BY presents a lower ID distribution in the 2.5 m to 6 m distance from the sprinkler compared to the two other models, except for the two cases showed in Figure II.6g and h, where the ID distribution of the RC130-BY was always larger than for the VYR35. This could be due to the difference in the main nozzle diameters for the two sprinkler models (5.0 mm for the RC130-BY and 4.8mm for the VYR35).

Three typical shapes of Rad have been reported in the literature: triangular, rectangular and donut. The triangular shape corresponds to the combinations of two nozzles, the rectangular shape to the combinations with one nozzle without SV, and the donut shape to the combinations with one nozzle and SV and with lower operating pressure (Tarjuelo et al., 1999a). The Rad for the presented models did not match any of the three typical shapes as they were rather combinations of them.

The paired samples analysis showed that only two Rad patterns were statistically similar: the RC130-BY (4.5mm; 300kPa) with the RC130-L (4.4mm; 300kPa) (figure II.6e). The other comparisons of the Rad for the different sprinkler models and combinations of D and p were different in shape.

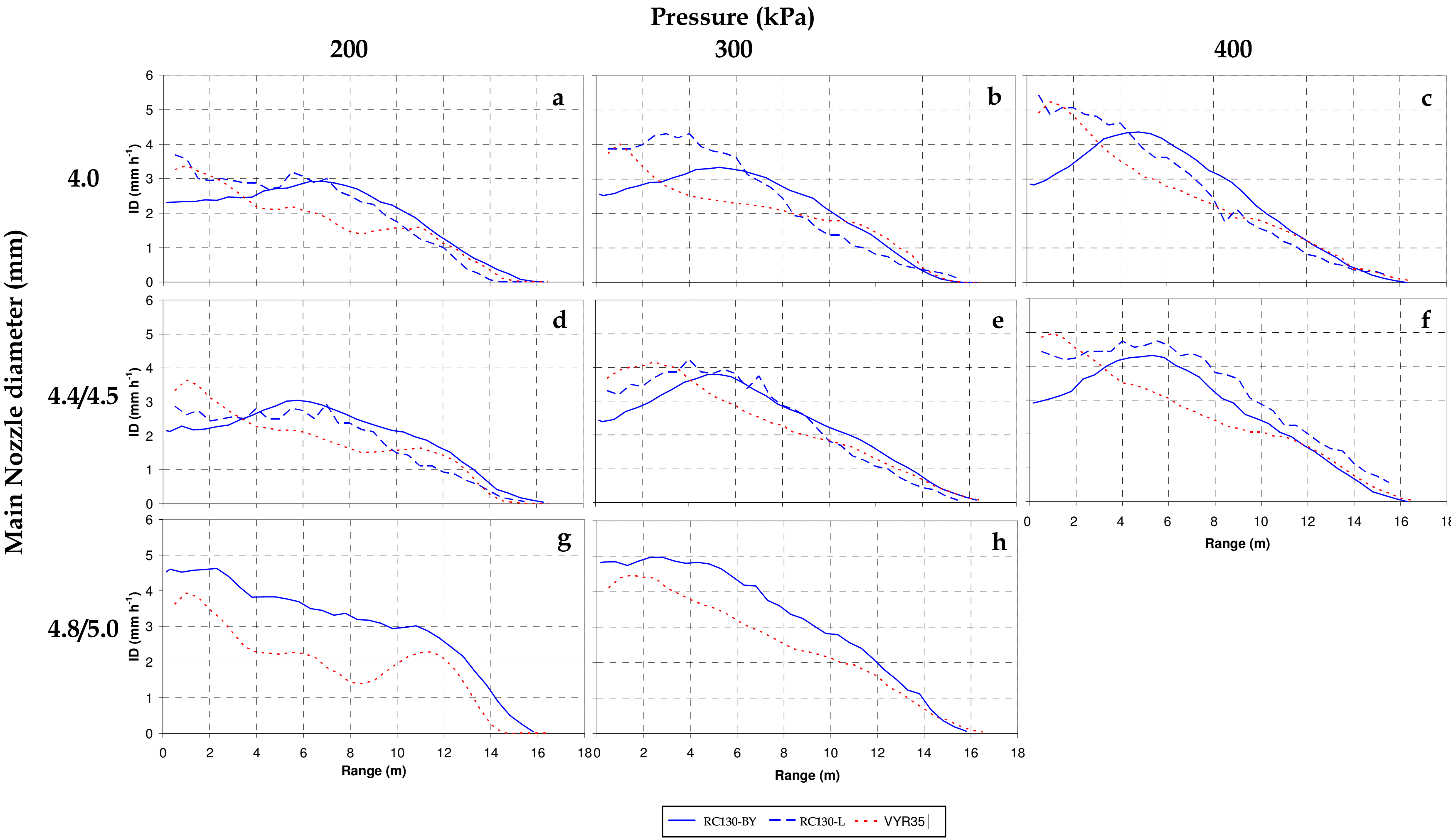

Figure II. 6. *Average irrigation depth (ID, mm h-1) collected along the wetted radius of the sprinkler (Rad) for the RC130-BY sprinkler with three main nozzle diameter (4, 4.5 and 5 mm) and three operating pressure. Radial curves of sprinkler models RC130-L and VYR-35 are included for comparison purposes. Main nozzle diameters of RC130-L were 4 and 4.4 mm. Main nozzle diameters of VYR35 were 4, 4.4 and 4.8 mm. In all cases an auxiliary nozzle was used (2.5 mm in the RC130-BY and 2.4 mm in the RC130-L and VYR35).*

II. 3.3 Solid-set experiment

Fifty tests corresponding to different combinations of D, p were performed in the solid-set experiment using the sprinkler model RC130-BY to analyze their effects on the CUC and on the WDEL. The tests were performed under an ample range of meteorological conditions. Operating pressure in the different solid set evaluations varied between 188 and 392 kPa (Table II.2). The average duration of the solid set evaluations was around 2.2 h (± 0.31h) and varied from a minimum of 1.6 h to a maximum of 3.27 h. The wind speed in the different evaluations varied between 0.16 and 7.60 m s^{-1}. The average temperature of the evaluations was 21.7ºC ranging from 7.8 to 30.1 ºC. In general the evaluations of the solid set for different main nozzle diameters were performed for similar conditions of air temperature and relative humidity except in a few individual evaluations of the 4+2.5 and 5+2.5 mm nozzle diameters where the temperature was significantly lower than the average.

The performance parameters CUC and WDEL of the solid set evaluations showed an ample range of variation. CUC of individual evaluations varied from 51% to 93% and WDEL varied from 0% to 36% depending mainly on the operation and meteorological conditions.

The effects of wind speed (U), main nozzle diameter (D), operating pressure (p) and other meteorological variables on CUC and on WDEL were assessed using backward stepwise analysis to select the best suited model for the prediction of these parameters in solid set with the sprinkler model RC130-BY.

The best model found for the prediction of the CUC was the following equation:

$$CUC\ (\%) = 90.30 - 4.40*U \qquad (R^2_{adj}= 75\%;\ RMSE= 1.9\%) \qquad (II.5)$$

The best fit between the wind speed and the CUC was obtained with a linear regression function (Figure II.7) that describes the negative relationship between the CUC and the independent variable U. The increase of U will induce an important decrease on the CUC. A relatively high adjusted coefficient of determination was obtained for the CUC equation (R^2_{adj}=0.75). The relationship depicted on Equation II.5 shows the best suited equation obtained by backward stepwise method to predict the CUC according to its explicative and predictive capabilities and its statistical significance (α lower than 0.01). The mean absolute error (MAE) for this equation was very low, less than 0.05%, the coefficient of efficiency (E) and the Similarity Index (IS) were 0.7 and 1.0 respectively and very close to 1.0 presenting a better agreement between observed and predicted CUC values. The Pred [0.25] indicates that the 100% of the predicted CUC differed from the measured CUC by less than 25%.

Table II. 2. *Summary of the 50 solid set tests performed for the sprinkler model RC130-BY arranged in a rectangular solid-set at 18 m by 18 m (R18×18). Experiments were grouped according to nozzle diameters (D+d, mm) and operation pressure range (around 200, 300 and 400 kPa). For each group the number of tests and the maximum and minimum values of operation pressure (p, kPa), irrigation time (IT, h), the uniformity coefficient of Christiansen (CUC, %), wind drift and evaporation losses (WDEL, %), wind speed (U, %), air temperature (T, ºC) and relative humidity (RH, %) of the air are presented.*

D+d (mm)	Number of tests	p (kPa)		IT (h)		CUC (%)		WDEL (%)		U (m s^{-1})		T (ºC)		HR (%)	
		Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
	5	208	190	2.06	2.0	85	65	27.8	10.7	5.86	1.47	24.9	21.3	57	44
4+2.5	5	328	305	2.65	2.0	90	61	25.7	8.2	5.78	1.42	26.5	7.8	80	42
	4	379	366	2.34	2.0	91	66	36.0	10.1	7.60	1.04	30.1	21.0	6	37
	6	206	188	2.07	1.6	82	70	21.0	0.0	4.01	0.48	30.0	18.8	66	41
4.5+2.5	7	344	285	2.75	1.8	93	51	15.0	2.0	5.77	1.05	26.0	21.0	60	50
	4	392	365	3.27	1.6	91	79	22.6	0.0	4.12	0.58	29.0	24.5	72	43
	8	222	191	2.57	1.9	84	72	21.8	0.0	5.02	0.16	26.0	9.0	75	45
5+2.5	5	326	291	3.01	2.1	91	75	19.0	0.7	5.03	1.40	26.3	12.0	74	43
	6	367	363	2.61	2.0	79	66	27.8	0.0	7.06	0.40	24.4	11.4	69	39

Figure II.7 presents the linear regression data of equation (II.5) between the CUC values obtained in the 50 solid set evaluations equipped with the RC130-BY sprinkler and wind speed (note that in Figure II.7, the value of the determination coefficient is slightly higher than the adjusted determination coefficient of equation II.5). In the Figure II.7 the relationship found by Playán et al. (2006) for solid set with the sprinkler model RC130-L with nozzle diameters of 4.4+2.5 mm is also presented for comparison purposes (dashed line). Both equations are similar in slope but the line of the RC130-L shows a higher CUC than the RC130-BY for the same level of wind speed ranged between 0.6 and 4.4 m s^{-1}.

Several studies have shown that the wind is the main environmental factor affecting sprinkler irrigation performance (Seginer et al., 1991a y 1991b; Kincaid et al., 1996; Dechmi et al., 2003a, b; Playán et al., 2005; Sanchez et al., 2010a, b; Tarjuelo et al., 1999c; Yu et al., 2009; Sánchez et al., 2011; Stambouli et al, 2012). In agreement with these studies, the wind speed decreased the CUC (Figure II.7) and increased WDEL (Figure II.8).

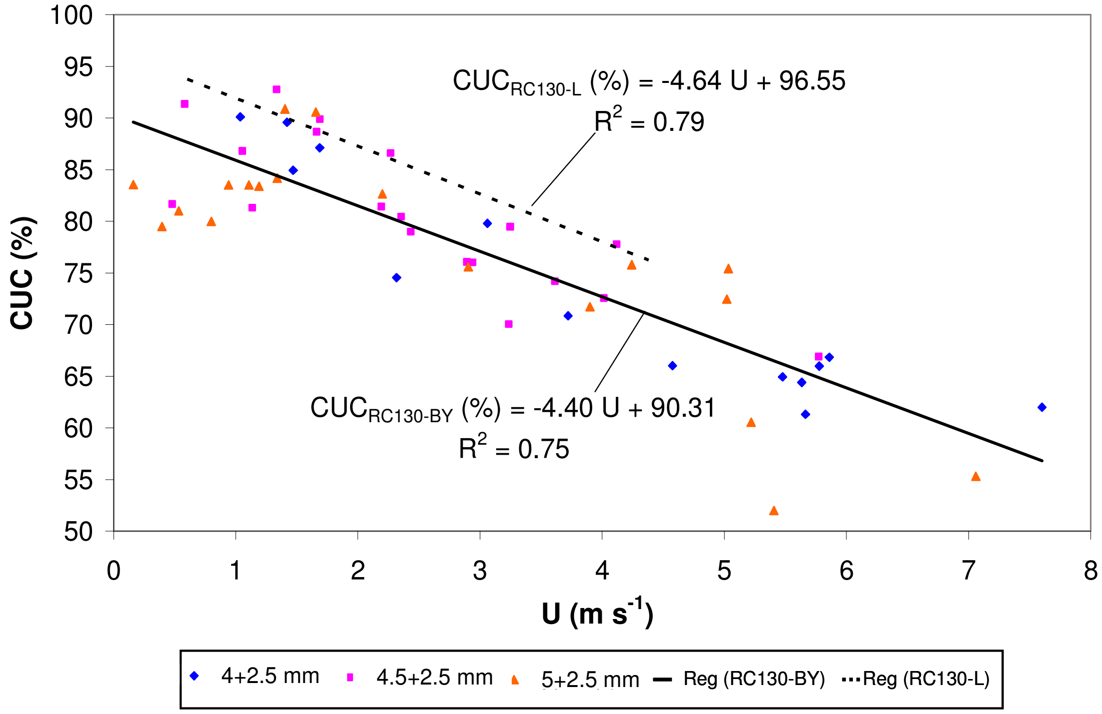

Figure II. 7. *Experimental relationship between wind speed and CUC for the RC130-BY arranged in a rectangular solid-set at 18 m by 18 m (R18 × 18). The different colors of the points correspond to different nozzle diameter D (4+2.5, 4.5+2.5 and 5+2.5 mm). Black line represents the linear regression of all experimental points. Dashed line represents the linear regression found by Playán et al. (2006) for a solid set with sprinkler RC130-L with nozzle diameter 4.4+2.4 mm, operating pressure ranging between 335 and 360 kPa at a triangular 18 m by 18 m spacing.*

The wind speed has also been reported by several authors (Playán et al., 2005; Zapata et al., 2007; Sánchez et al., 2011) as the most significant variable affecting the WDEL. However the selection of the predictor variables was more complicated in the case of the WDEL than in the case of CUC. When all the variables were included, only U and D were found significant (data not shown). Both variables have been previously selected among the predictor variables of the WDEL in other studies in sprinkler irrigation (Faci et al., 2001; Frost and Schwalen, 1955; Keller and Bliesner, 1990; Tarjuelo et al., 2000; Trimmer, 1987). The p was not significant in the present work although it has been included in many previous studies (Frost and Schwalen, 1955; Keller and Bliesner, 1990; Montero, 1999; Tarjuelo et al., 2000; Trimmer, 1987; Yazar, 1984).

The relationship between the wind speed and the WDEL showed that the data dispersion increases with the wind speed (Figure II.8). The best suited equation obtained to predict WDEL uses the wind speed and the nozzle diameter as the explicative variables (statistical significance α = 0.01) (Equation II.6).

$$WDEL\ (\%) = 22.31 - 4.56*D + 3.93*U \qquad (R^2_{adj}= 85\%;\ RMSE= 1.4\%) \qquad (II.6)$$

A relatively high adjusted coefficient of determination was obtained (R^2adj=0.85). MAE, IS, E and Pred [0.25] were 0.01, 0.99 and 0.9, 55% respectively. For conditions similar to those of this study, the regression equation obtained for all irrigation events to predict WDEL as a function of U and D would be recommended. However for comparison purposes of sprinkler models RC130-BY and RC130-L, the linear relationship between WDEL and U obtained with the experimental results of the solid set experiment is presented in Figure II.8. The determination coefficient (R^2) was 0.82, slightly lower than the value obtained when wind speed was included in the model (Equation II.6).

The linear regression found by Playán et al (2006) for a solid set with the model RC130-L with 4.4+2.4 mm nozzle diameters had a higher slope and lower value of the R^2. However the comparison is limited since the range of wind velocities in their solid set evaluations was narrower than in our evaluations.

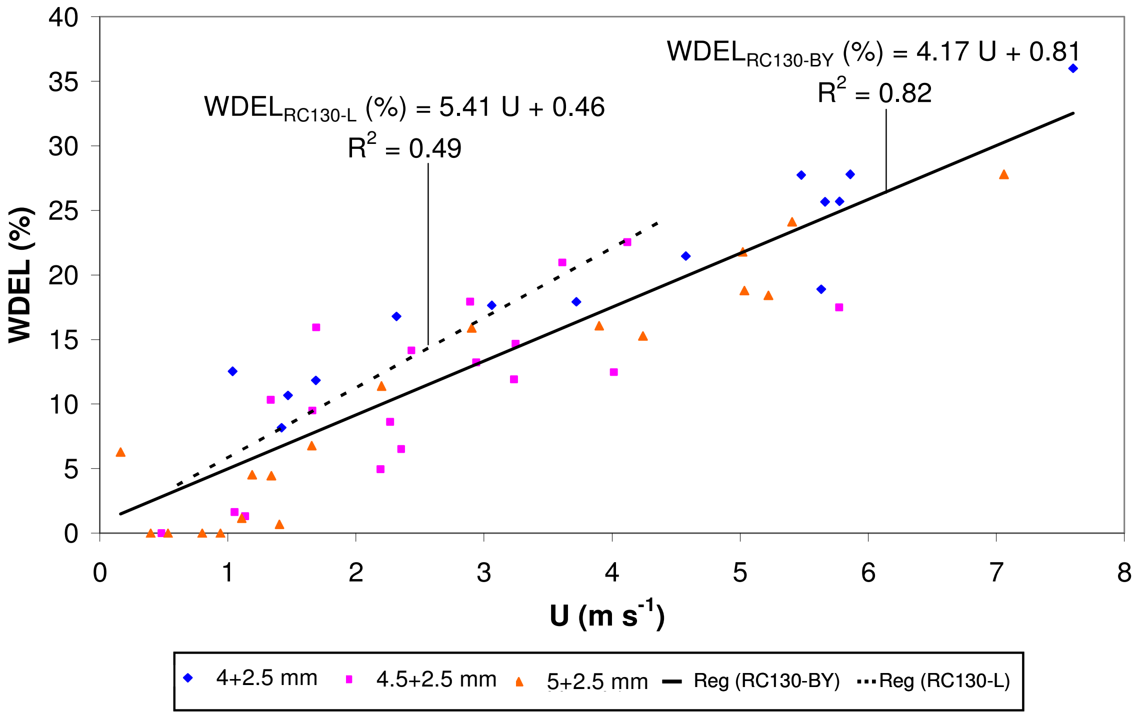

Figure II. 8. *Experimental relationship between wind speed and WDEL for the RC130-BY arranged in a rectangular solid-set at 18 m by 18 m (R18 × 18). The different colors of the points correspond to different nozzle diameter D (4+2.5, 4.5+2.5 and 5+2.5 mm). Black line represents the linear regression of all experimental points. Dashed line represents the linear regression found by Playán et al. (2006) for a solid set with sprinkler RC130-L with nozzle diameter 4.4+2.4 mm, operating pressure ranging between 335 and 360 kPa at a triangular 18 m by 18 m (T18x18) spacing.*

The importance of D and p in the performance of the sprinkler irrigation is explained through their effects on the atomization process. Recent investigations are focused on the atomization of the water jet released by the agricultural sprinklers (Bautista-Capetillo et al., 2009; King et al., 2010; Playán et al., 2010). The presented results prove the suitability of this line of research and point out that, in connection with this matter, D and p must be analyzed together.

II. 3.4. Comparison of the measured (RC130-BY) and simulated (RC130-L) irrigation performance of solid sets under the same operating and meteorological conditions.

A more detailed comparison between solid sets equipped with two sprinkler models (RC130-BY and RC130-L) of the same physical characteristics was performed.

In order to make a reliable comparison of the two sprinkler models, the same meteorological and operation conditions should be present in the evaluations. As no experimental data with the RC130-L were available under the same operation and meteorological conditions of our experiments with the RC130-BY, the irrigation performance indicators (CUC and WDEL) for the RC130-L sprinkler model, were simulated using the empirical model Ador-sprinkler (Playán et al., 2006). The same values of the operational and meteorological variables in our experiments (time of irrigation, operation pressure, wind speed and average wind direction, air temperature and relative humidity) were introduced in the Ador-sprinkler model for the calculations.

The comparison was established for D = 4.0+2.5 mm and 4.5+2.5 mm for the RC130-BY and D= 4.0+2.4 mm and 4.4+2.4 mm for the RC130-L. Table II.3 presents the experimental results of the solid set with sprinkler RC130-BY and simulated values of ID, WDEL and CUC for the sprinkler RC130-L under the same experimental conditions (Table II.3). No difference was found between the water discharges of both sprinkler models (data not showed). The very slight difference in the nozzle diameters (4.4+2.4 mm in the RC130-L and 4.5+2.5 mm in the RC130-BY) did not change the water discharge of both sprinklers.

In other studies, solid set sprinkler irrigation systems have been evaluated for different combinations of D and p (Playán et al., 2006; Tarjuelo et al., 1999b, 1999c; Sanchez et al., 2011). Some studies like that by Kincaid (1982) analyzed the combined effect of p and D on the water distribution of the sprinklers, however, others authors highlighted the effects of D and p separately. Kohl (1974) reported that the effect of D on the drop size distribution is smaller than the effect of p, apparently; the relationship between CUC and WDEL with the wind speed (U) was affected by D and p (Figure II.9). Apparently, these relationships differed depending on p, and the differences owing to p decreased with the D increasing.

Figure II.9 presents the comparison of the measured CUC and WDEL values of the experimental solid set equipped with sprinkler models RC130-BY and the simulated values for the same solid set with the RC130-L sprinkler under the same operational and meteorological conditions. The comparison showed that the CUC is relatively similar in both sprinkler models. The linear regression showed slightly higher values of CUC for the RC130-BY than for the RC130-L in the low range of CUC (< 70%) and lower values of CUC in the high range of CUC (>70%). These results may be explained by a difference in the sprinkler models behavior with the wind speed (U). In table II.3 the comparison between CUC values of the RC130-BY and the RC130-L for wind speed (U) < 1.5 m s^{-1}, showed that the CUC for the two sprinkler models were almost equal (average difference in CUC was in order of 1.2 %). When U ranged between 1.5 and 4 m s^{-1}, difference in CUC between the two models was very high (average difference in CUC was around 10%) and the RC130-L model showed higher CUC values. For high wind speed (U > 4 m s^{-1}), the difference in CUC between the two models was moderate (average difference in CUC was around 4%) and the CUC of RC130-BY model was higher than the RC130-L model.

The linear regression of WDEL for both sprinkler models had a regression coefficient of 2.72 (R^2 =0.75) showing a clear separation of the line 1:1. In the low range of WDEL (<21%) the WDEL for the RC130-BY was lower than for the RC130-L and for the high range of WDEL (>21%) the opposite occurred. The higher experimental values of WDEL for the RC130-BY compared to the simulated values of WDEL for the RC130-L were mainly due to the prediction equation used in the Ador sprinkler simulation model. This equation to determine WDEL includes a constant value of 15% even under totally calm conditions and in our experimental conditions measurements of WDEL were frequently lower than this threshold value under calm or low wind speed.

Table II. 3. *Comparison of measured irrigation performance parameters (uniformity coefficient of Christiansen, CUC, and wind drift and evaporation losses, WDEL) in the experimental solid set (R18x18) with the sprinkler RC130-BY and the simulated values of CUC and WDEL for the same solid set arrangement (R18x18) with the sprinkler RC130-L under the same experimental values of irrigation time (IT), pressure (p), Wind speed (U) and direction (WD), air temperature (T) and relative humidity (HR).*

							Measured RC130-BY			Simulated RC130-L		
D+d *(mm)*	**IT** *(h)*	**p** *(kPa)*	**U** *(m s⁻¹)*	**WD***	**T** *(°C)*	**HR** *(%)*	**ID** *(mm)*	**WDEL** *(%)*	**CUC** *(%)*	**ID** *(mm)*	**WDEL** *(%)*	**CUC** *(%)*
4+2.5	2.07	190	3.72	NW	21.3	54	7.59	17.9	71	7.70	17.7	80
	2.13	202	1.47	E	21.8	57	8.06	10.7	85	8.00	13.8	86
	1.99	202	5.86	NW	23.3	52	7.54	27.8	67	7.40	21.1	61
	1.99	305	5.78	NW	26.5	42	9.25	25.7	66	9.10	23.2	67
	1.97	310	1.42	E	25.5	47.5	9.24	8.2	90	9.00	15.8	90
	2.65	316	2.32	W	7.8	81	12.55	16.8	75	12.10	9.9	80
	1.98	367	1.04	SW	30.9	37	10.13	12.5	90	10.10	17.6	92
	2.27	379	7.60	NW	18.5	51	11.75	36.0	62	11.60	23.8	60
4.5+2.5	1.58	188	4.01	NNW	18.8	66	6.89	12.5	73	6.80	15.5	87
	1.75	194	0.48	NE	21.7	63	7.74	0.0	82	7.60	11.2	85
	2.07	205	2.89	WSW	29.9	41	9.39	17.9	76	8.90	19.4	90
	2.75	292	1.66	SSE	24.8	58	14.90	9.5	89	14.50	14.0	92
	2.01	302	5.77	NW	21.1	50	11.06	17.5	67	10.60	21.4	65
	2.42	305	2.94	WSW	24.9	60	13.39	13.2	76	12.80	15.3	88
	3.27	365	4.12	NW	28.9	43	19.79	22.5	78	19.30	20.6	71
	1.58	385	0.58	NW	22.3	72	9.86	0.0	91	9.60	9.3	91
	2.42	392	2.35	S	24.5	72	15.17	6.5	80	14.80	11.8	93

* *Prevailing wind direction*

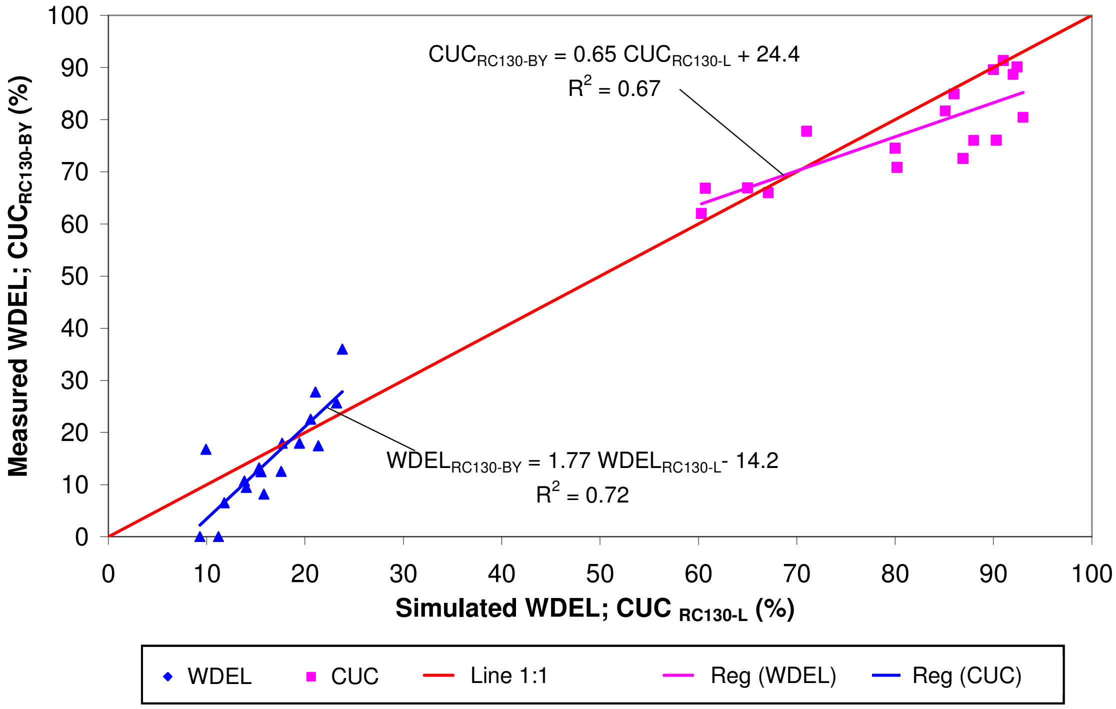

Figure II. 9. *Linear regressions of measured WDEL and CUC in the experimental solid set evaluations with the RC130-BY sprinkler model versus the corresponding values of simulated WDEL and CUC with the Ador sprinkler model for the same solid set arrangement and operation conditions with the RC130-L sprinkler model. Red line represents the 1:1 line. Regression equations are presented in the Figure.*

The results obtained in this work showed that the selection of the sprinkler model is very complicated since its performance depends on many factors of different nature, many of them out of the control of the farmer. The knowledge of the radial curve of the sprinkler and empirical models as Ador-sprinkler are extremely useful tools for decision making as they allow the simulation of the sprinkler irrigation performance under very different conditions. However, thorough investigations are needed to acquire a better understanding about the processes involved in the formation and the atomization of the jet and the evaporation and the drift of the resulting water drops. This is the path towards physical models valuable for the manufacturers of agricultural sprinklers, for the farmers and for the whole society that needs and demands an efficient use of the water.

Figure II.10 presents a comparison of the water distribution patterns measured in various experiments with the RC130-BY sprinkler model with the simulated water distribution patterns for the RC130-L sprinkler model. Under low wind conditions (U=1.6 m s-1) (Figure II.10. a and b) a very high uniformity distribution was observed (CUC of 89 % and 92 % for RC130-L and RC130-BY, respectively) is observed in both sprinklers. Under moderate wind conditions (U=2.9 m s-1) (Figure II.10, c and d) a lower value of CUC for the RC130-BY

(76%) than the simulated CUC for the RC130-L (88%) was observed. For high wind conditions (U=5.8 m s^{-1}) (Figure II.10, e and f) a slightly higher CUC was obtained for the RC130-BY model. The irrigation uniformity decreased with the wind speed (U). It can be observed (particularly in Figures II.10. c, d, e and f) that the wind distortion of the water distribution pattern concentrates precipitation in particular areas of the experimental field.

The water distribution pattern of a sprinkler layout is the result of the overlapping of the jets of water emitted by the sprinklers. Tarjuelo et al. (1999b) and Keller and Bliesner (1990) showed that water distribution pattern of solid set sprinkler irrigation systems was dependent on technical and meteorological conditions. For design purposes, the sprinkler model, the nozzles sizes, the operation pressure, the sprinkler layout and the sprinkler height above the soil are variables that should be considered.

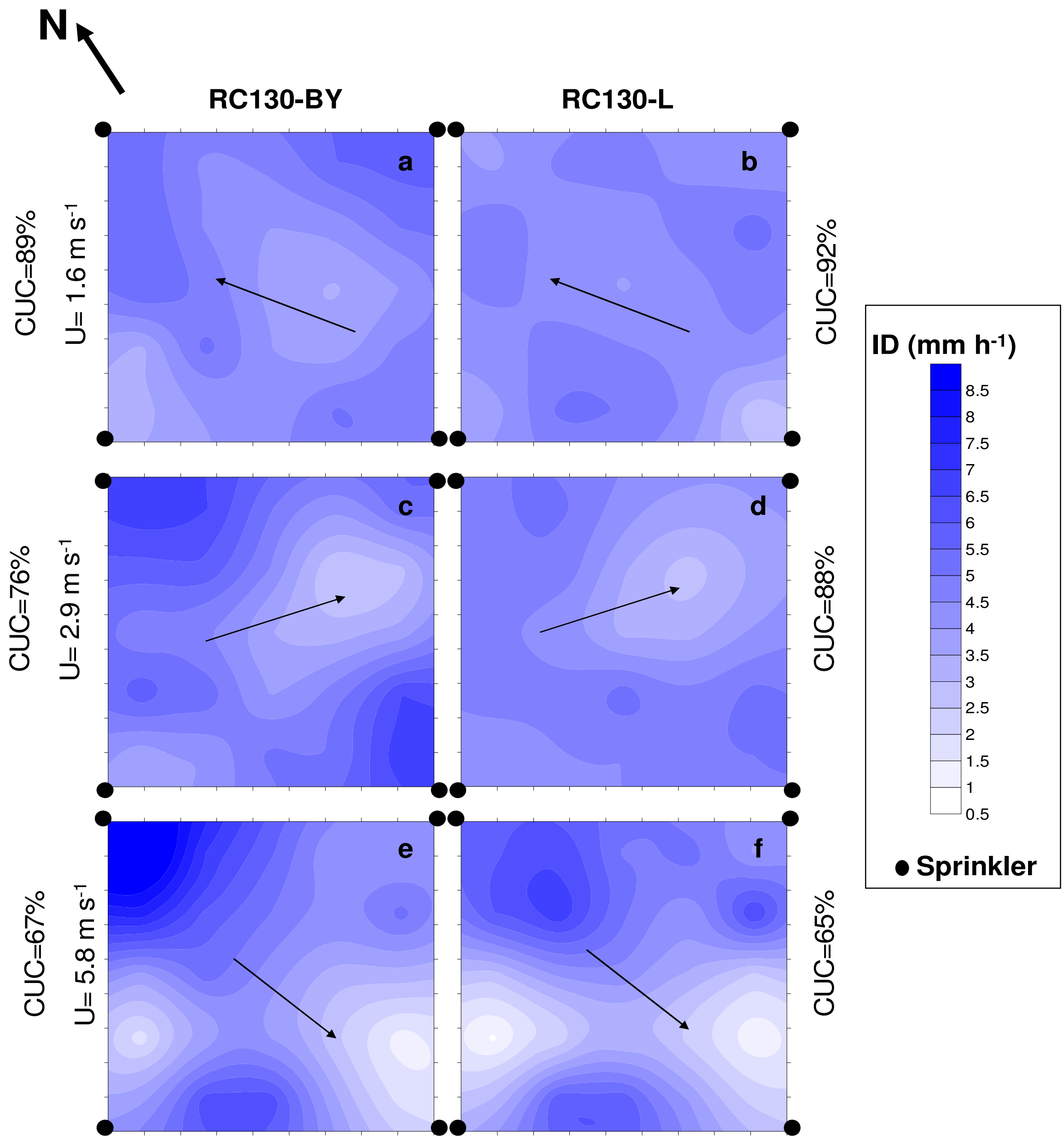

Figure II. 10. *Water distribution pattern (ID, mm h*$^{-1}$*) contour line maps for the evaluated sprinkler model RC130-BY and for the RC130-L for the combination of p= 300kPa and D = 4.5 mm (4.4 mm for the RC130-L) and under several wind speed (U). Sub-figures II.10.a, II.10.c, and II.10.e, present the spatial variability of the ID measured for the RC130-BY, sub-figures II.10.b, II.10.d and II.10.f present the spatial variability of the ID simulated with the Ador-Sprinkler simulation model for the RC130-L. Arrows indicate the prevailing wind direction during each event. CUC (%) were indicated for all combinations.*

II. 4. CONCLUSIONS

The water distribution in a solid set spacing depends greatly on the shape of the radial curve (Rad) of the sprinkler selected. The information given in the sprinkler catalogs by sprinkler companies very often is limited and insufficient for sprinkler design purposes. The technical information of the Rad should be included in sprinkler technical information since this information is very convenient for an optimal sprinkler design.

The results showed that characterization of the Rad of impact sprinkler with plastic nozzles in sprinkler isolated tests in open air conditions implies several precautions because the wind significantly distorts the Rad. As found previously by Sanchez et al. (2011) with impact sprinklers with brass nozzles, it is recommended that evaluation tests of isolated sprinkler should be performed with wind speeds lower than 0.6 m s^{-1}. Otherwise, the resulting Rad will not be suitable and it will conduct to erroneous results. Therefore only the results of water distribution under very low wind speed were considered in our isolated sprinkler tests for the determination of the Rad.

The introduction of new sprinkler with plastic nozzles in the sprinkler solid set systems offer some advantages to the farmers but a detailed analysis of this type of sprinkler is needed in order to know the reliability of them. The comparison of the Rad of the plastic nozzle sprinkler (RC130-BY) with the same sprinkler model but with brass nozzles (RC130-L) showed in general different shape of the Rad. Only for the nozzle diameters of 4.4+2.5 mm at 200 and 300 kPa the Rad was similar in the RC130-BY and the RC130-L.

The CUC of a solid set can be calculated for different wind conditions using sprinkler simulation models, but the model should include calibration and validation of this particular material and the characterization of the Rad is necessary anyhow.

As previously reported in other studies for impact sprinklers, a linear relationship was found between the CUC the wind speed (U) for our results of the experimental solid set equipped with plastic nozzles sprinklers (R^2_{adj} = 75%; RMSE = 1.9%). However the best suited regression equation to predict WDEL uses the wind speed (U) and the nozzle diameter (D) as the explicative variables for the experimental solid set (R^2_{adj} = 85%; RMSE = 1.4%). It must be noticed that these functions are restricted to a specific sprinkler design and to a solid-set arrangement.

The comparison of the measured CUC values of the experimental solid set (R18x18) equipped with sprinkler model RC130-BY and the experimental solid set (T18x18) with the RC130-L of Playán et al. (2006) showed that CUC values of the RC130-L model were in order of 5% higher than the RC130-BY model. With these comparisons, the RC130-L model seems better than the RC130-BY model, however, this comparison is limited because Playán et al. (2006) evaluated the RC130-L with only a main nozzle diameter of 4.4, p ranging between 328 and 350 kPa, U ranged between 0.6 to 4.4 m s^{-1} and in a solid set configuration of T 18X18.

The comparison of the measured CUC values of the experimental solid set equipped with sprinkler model RC130-BY and the simulated values for the same solid set with the RC130-L sprinkler, showed interesting patterns. The linear relations were not coincident with the line 1:1 showing a different performance of both types of sprinklers when the operation and meteorological conditions change. In low wind conditions, the CUC of the two sprinkler models was similar and high (average CUC of 89%). However in medium wind conditions (1.5m s^{-1} ≤ U ≤ 4.0 m s^{-1}) the CUC of the RC130-BY model was more affected (average of 78%) than the RC130-L (average CUC of 87%) and in high windy conditions (U ≥ 4 m s^{-1}), the RC130-BY presents better CUC values.

The results presented show that the choice of the sprinkler model is very complicated because it depends on many factors, and many of these factors are out of the control of the farmer. Empirical models such as Ador-sprinkler are extremely useful tools for decision making as they allow the simulation of the sprinkler irrigation performance under very different operational and meteorological conditions. The specific information of the sprinkler used in this study will be included in the Ador-sprinkler model to allow the simulation of the RC130-BY sprinkler model.

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CHAPTER III: SPRINKLER EVAPORATION LOSSES IN ALFALFA DURING SOLID-SET SPRINKLER IRRIGATION IN SEMI-ARID AREAS

SPRINKLER EVAPORATION LOSSES IN ALFALFA DURING SOLID-SET SPRINKLER IRRIGATION IN SEMI ARID AREAS

RESUMEN

Las pérdidas brutas por evaporación en riego por aspersión (SEL_g) pueden ser elevadas reduciendo de forma significativa la eficiencia del riego. Sin embargo, no se conoce claramente cual es la contribución de SEL_g a la disminución de la evapotranspiración (ET) del cultivo durante el riego por aspersión y cuánto suponen las pérdidas por evaporación netas en riego por aspersión (SEL_n). Los componentes de las pérdidas por evaporación en riego por aspersión (SEL) son las pérdidas por evaporación y arrastre (WDEL) y las pérdidas por intercepción del cultivo (IL). En el presente trabajo las WDEL brutas ($WDEL_g$) y la evapotranspiración del cultivo (ET) se midieron simultáneamente en dos parcelas cultivadas de alfalfa (Medicago sativa L.), una se regaba durante las medidas (tratamiento regado, MT) y la otra no se regaba pero las medidas se hicieron al mismo tiempo (tratamiento seco, DT). Ambas parcelas se regaron con una cobertura fija de riego por aspersión aplicando una cantidad suficiente de agua para satisfacer las necesidades hídricas de los cultivos durante toda la campaña. Las parcelas experimentales de 1 ha de superficie cada una de ellas son adyacentes y cada una dispone de un lisímetro de pesada en su parte central. Los experimentos se llevaron a cabo durante el año 2009, en Montañana (Zaragoza, NE España). Para la medida de $WDEL_g$ se instaló una red de 25 pluviómetros en un marco de riego (entre 4 aspersores) en ambas parcelas. Se midió el agua recogida en los pluviómetros, las ganancias y pérdidas de las masas en los lisímetros de pesada así como las variables micro-meteorológicas para calcular las pérdidas por evaporación y arrastre netas ($WDEL_n$) durante el riego y las pérdidas por intercepción netas (IL_n) después del riego como la diferencia entre ET_{MT} y ET_{DT}. Se desarrollaron ecuaciones lineales para determinar de forma sencilla las IL_n y las SEL_n. Los resultados mostraron que la reducción media de ET fue de 0,90 mm por evento de riego para los riegos diurnos y de 21,6 mm para el conjunto de los 24 eventos de riegos diurnos que representa un 4,3% del total de agua aplicada. Para los riegos nocturnos, esta contribución fue menor, de 0,15 mm por evento de riego y de 1,9 mm para el conjunto de los 12 eventos de riegos nocturnos, que representa el 0,8% del total de agua aplicada. Esta reducción de la ET puede ser beneficiosa para los cultivos, especialmente durante el riego diurno. Las IL_n se calcularon de 1 a 3 horas después de los eventos de riego y representaron el 2,9% del agua total en los en 36 eventos de riego. Las IL_n estuvieron muy relacionadas con el déficit de presión de vapor (VPD). Las SEL_n representaron el 8,3% del agua aplicada total. Durante los riegos diurnos, las SEL_n fueron del 9,8% del agua aplicada, algo menor que las $WDEL_g$ (10,9%). Durante los riegos nocturnos, las SEL_n fueron ligeramente mayores que WDELg (5,4% y 3,7%, respectivamente). La variable que más afectó al valor de SEL_n fue la velocidad del viento.

PALABRAS CLAVE
Pérdidas por evaporación y arrastre, pérdidas por intercepción, las pérdidas por evaporación en riego por aspersión, lisímetros de pesada, riegos día / noche, cambios microclimáticos y fisiológicos.

ABSTRACT

Gross sprinkler evaporation losses (SEL_g) during sprinkler irrigation can be large and decrease irrigation application efficiency. However, it is not universally established how much of the SEL_g contributes to decrease the crop evapotranspiration during the application of water in sprinkler irrigation and how much are the net sprinkler losses (SEL_n). The components of SEL were the wind drift and evaporation losses (WDEL) and the water intercepted by the crop (IL). In this work the gross wind drift and evaporation losses ($WDEL_g$), the net intercepted losses (IL_n) and evapotranspiration (ET) were measured simultaneously in two alfalfa (Medicago sativa L.) plots, one being irrigated (moist treatment, MT) and the other one not being irrigated (dry treatment, DT). Both plots were irrigated by solid-set sprinkler irrigation systems with enough water to supply the crop water requirements during the crop season. The plots were located in adjacent fields and each of them had a weighing lysimeter. Experiments were conducted during 2009 in Montañana (Zaragoza, NE Spain). A network of 25 catch cans was installed in an irrigation framework (between four sprinklers) and in each plot allows measuring the $WDEL_g$. Catch can measurements, mass gains and losses in the lysimeters and micrometeorological measurements were performed to establish net WDEL ($WDEL_n$) and net IL (IL_n) after the irrigation as the difference between ET_{MT} and ET_{DT}. Also, models to estimate IL_n and net sprinkler evaporation losses (SEL_n) were developed. Results showed that the average ET reduction was 0.90 mm per daytime irrigation event, 21.6 mm for the 24 daytime irrigation events that equaled to 4.3% of total applied water. For nighttime irrigation, this contribution was less, 0.15 mm per irrigation event and 1.9 mm considering the 12 nighttime irrigation events, that corresponds to 0.8% of total applied water. This ET reduction may be beneficial for crop, especially during the daytime irrigation. IL_n was computed from 1 to 3 hours after irrigation events and summed 2.9% of the total irrigation water during 36 irrigation events. The IL_n was strongly related to vapor pressure deficit (VPD). Net sprinkler evaporation losses (SEL_n) were 8.3% of the total applied water, for both day and nighttime irrigation events. During daytime irrigations, SEL_n was 9.8% of the irrigation water and slightly lower than $WDEL_g$ (10.9%). During nighttime irrigations SEL_n were slightly greater than $WDEL_g$ (5.4% and 3.7%, respectively). SEL_n was mainly a function of wind speed.

KEY WORDS

Wind drift and evaporation losses, interception losses, Sprinkler evaporation losses, Weighing lysimeters, Day/night time irrigation, Microclimatic and Physiological changes.

ABREVIATIONS

ai	=After irrigation
AMRE	=Average Magnitude of Relative Error
$CU_{0.85m}$	= Christiansen's Uniformity Coefficient calculated with catch cans at 0.85 m above ground level (%)
CU_{2m}	= Christiansen's Uniformity Coefficient calculated with catch cans at 2 m above ground level (%)
CV	= Coefficient of variation
d1	= Large nozzle diameter (mm)
d2	= Small nozzle diameter (mm)
D_C	= Discharge coefficient (= 0.98)
di	= During irrigation
DT	= Dry treatment
E	= Coefficient of Efficiency
EF	= Water application efficiency (%)
EP	= Effective precipitation (mm)
ET_o	= Reference evapotranspiration (mm)
ET_c	= Crop evapotranspiration (mm)
ET_{DT}	= Evapotranspiration rate of the dry treatment plot (mm h^{-1})
ET_{MT}	= Evapotranspiration rate of the moist treatment plot (mm h^{-1})
g	= Gravity acceleration (m s^{-2})
H	= Nozzle height (m)
I_{cc}	= Irrigation depth collected in the catch can (mm)
I_g	= Gross irrigation depth (mm)
I_{lcc}	= Irrigation depth collected in the lysimeter (mm)
I_{lq}	= Irrigation application for the lowest quarter of the field (mm)
I_{lys}	= irrigation depth recorded by the lysimeter (mm)
IL	= Intercepted losses (% or mm)
IL_g	= Gross Intercepted losses (% or mm)
IL_n	= Net interception losses (% or mm)
IS	= Similarity Index
k	= Total Irrigation duration (hours)
K_c	= Crop coefficient

MAE	= Mean average error
MSE	= Mean square error
m	= Time after irrigation event considered to compute the IL_n (hours)
MT	= Moist treatment
NIR	= Net irrigation requirements (mm)
P	= Pressure at the nozzle (kPa)
Pred [0.25]	= The level of prediction to 25 %
Q	= Sprinkler flow rate (l s^{-1})
R^2	= Coefficient of determination
RH	= Air relative humidity (%)
S	= Area irrigated by one sprinkler (m^2)
SEL	= Sprinkler evaporation losses (mm or %)
SEL_n	= Net sprinkler evaporation losses (mm or %)
T	= Air temperature (ºC)
TV	= Canopy temperature (ºC)
t	= Operating time of the irrigation event (s, h)
WDEL	= Wind drift and evaporation losses (%)
$WDEL_g$	= Gross wind drift and evaporation losses (%)
$WDEL_n$	= Net wind drift and evaporation losses (%)
U	= Wind speed (m s^{-1})
VPD	= Vapor pressure deficit (kPa)
$\Delta WDEL_g$	= Difference between $WDEL_g$ measured a 0.85 m and at 2 m height above ground level.

III.1. INTRODUCTION

Irrigation has an important role to increase and stabilize the crop yield, while the application efficiency plays an important role to select a suitable irrigation method and scheduling in arid and semi-arid regions. A fraction of the water applied by the sprinkler nozzles is lost by evaporation before reaching the soil during sprinkler irrigation events. These sprinkler evaporation losses (SEL) can be divided in wind drift and evaporation losses (WDEL) and interception losses (IL).

$$SEL = WDEL + IL \tag{III.1}$$

WDEL represent the water lost during the travel of the water droplets from the sprinkler nozzle to the surface being irrigated. Some of these losses drift out the irrigated area. Nevertheless, all this water is eventually lost to evaporation. Some water droplets reach the crop leaves and stems but evaporate before reaching the soil surface. These latter losses represent the IL.

Previous works have reported different values and predictive models for WDEL depending upon different experimental conditions: sprinkler spacing, operating pressure, nozzle diameter, and, particularly, meteorological conditions (wind speed, water vapor pressure deficit and temperature) (Yazar, 1984; Tarjuelo et al., 2000). Edling (1985) and Thompson et al., (1993a) found that WDEL were inversely proportional to the diameter of the droplets which in turn depend, among others, on nozzle diameter and nozzle operating pressure (Kohl and Wright 1974; Solomon et al., 1985). Lorenzini, (2004) and De Wrachien and Lorenzini, (2006) indicated that evaporation losses were directly proportional to droplet diameter considering the effects of air friction (ignored in previous models) on droplet evaporation which is relevant under the turbulent flow commonly found at the boundary layer. Thus, values of WDEL up to 30 to 50% of the applied water have been reported in the Middle Ebro River Valley located in the north-eastern of Spain (Playán et al., 2005). Wind speed and, at a lesser extent, relative humidity have been found to be the most important meteorological factors affecting WDEL (Playán et al., 2005).

By the other hand, IL depends on the water storage capacity of a crop which in turn depends on its architecture. Several authors have reported IL values for maize (*Zea mays* L.) of about 2.5 to 2.7 mm (Fritschen, 1960; Seginer, 1967; Smajstrla and Hanson, 1980; Norman and Campbell, 1983; Steiner et al., 1983a). Lamm and Manges (2000) estimated an average value of IL of 1.8 mm. For sprinkler irrigation, IL is quantitatively smaller than WDEL, particularly for long irrigation events, as typical solid-set sprinkler irrigation depths range between 10 to 50 mm.

Due to the water lost to evaporation, the crop microclimate changes during and just after sprinkler irrigation, i.e. the air temperature (T) and the vapor pressure deficit (VPD) decrease (Robinson 1970; Steiner et al., 1983b; Tolk et al., 1995). For maize, this microclimate change only last a few hours after the irrigation event (Tolk et al., 1995; Cavero et al., 2009). The decline in the VPD, during and after sprinkler irrigation, would lead to a certain reduction of the crop transpiration rate. This would result in the conservation of soil water which would otherwise be depleted by the crop (McNaughton, 1981; Steiner et al., 1983a). Assessment of the effect of sprinkler irrigation on soil evaporation (E) is more difficult. The increase in soil water and the presence of ponded water over the soil could result in an increased potential for evaporation. However, the reduction in the evaporative demand of the air, due to the reduction of VPD, will induce a decrease in the evaporation flux. Nevertheless, the ratio of soil evaporation to crop evapotranspiration (ET = E + T) in fully developed canopies is low.

Following McNaughton, (1981), any reduction in crop ET from a wetted surface (compared to that from a dry area not being irrigated simultaneously but kept under similar water availability conditions) can be subtracted from the gross irrigation water losses to estimate the net irrigation water losses. At first glance, SEL are considered consumptive, non-beneficial water use (Burt et al., 1997). However, the part of SEL replacing crop ET should be regarded as consumptive and beneficial (McNaughton, 1981). This results in the introduction of gross and net sprinkler evaporation losses (SEL_g and SEL_n). Eq. (1) is valid for both gross and net losses. Taking into account net evaporation losses instead of gross evaporation losses could lead to an increase of application efficiency for a given application depth (Martínez-Cob et al. 2008).

The differences in ET rates between wet and dry surfaces just after irrigation events have been the object of several studies. Similar ET rates for both wet and dry crops have been reported by McMillan and Burgy (1960), Frost (1963), and Seginer, (1967). Waggoner et al., (1969) reported short-term ET rates of wet maize canopies more than twice that of dry maize canopies during the typical summertime conditions in Connecticut (USA). This difference only lasted for about 15 minutes, after which the ET rates became similar for both canopies. Less information is available regarding to the differences in ET rates between wet and dry surfaces during the irrigation events themselves. Frost and Schwalen (1960) found that dry-leaf ET equaled or exceeded wet-leaf ET (both measured by weighing lysimeters) under similar atmospheric conditions. Sternberg, (1967) reported that rye-grass ET (also measured by weighing lysimeters) was almost suppressed during irrigation and decreased by about 33 % after irrigation, as compared to that of a non-irrigated lysimeter. Tolk et al., (1995) found a 36-41 % reduction of maize transpiration during two daytime irrigation events using a lateral move sprinkler irrigation system in Texas (USA). Tolk et al., (1995) used an energy balance based method to quantify evaporation rates and net irrigation water depth. What these authors called interception losses were likely reflecting total SEL rather than IL because the energy balance as applied by Tolk et al., (1995) would not allow separating WDEL from IL. Martínez-Cob et al., (2008) analyzed 21 irrigation events and found average reductions of maize transpiration of 58 %, and ET of 32-55 % for wet surfaces during daytime solid-set sprinkler irrigation events.

After the irrigation events, the average reduction of maize transpiration was about 20 %, while ET for the wet surface was about 35 % higher than that of the dry surface, reflecting the net interception losses (IL_n) just after the irrigation events. Those differences between the wet and dry surfaces only lasted about 1 to 2 h after the irrigation. Nevertheless, the IL_n only amounted 1 % of the applied water. During the irrigation event, the sharp decrease of VPD observed, lead to a lower water vapor gradient between the evaporating surface and the atmosphere layer next to it (Martinez-Cob et al., 2008). The ratio of canopy to aerodynamic resistances is also low, so that the reduction of transpiration almost voids the increased evaporation of intercepted water (Monteith 1981; Steiner et al., 1983a). For these reasons, interception losses during irrigation time were small enough to be considered as negligible (Martínez-Cob et al., 2008).

No much information is available on the possible reduction of alfalfa (*Medicago sativa L.*) ET during and after sprinkler irrigation. There is some evidence of the possible influence of the wettability of leaves on the gas exchange of different crops under sprinkler irrigation. Thus Cavero et al., (2010) reported a different wettability of maize and alfalfa leaves affecting the change of net photosynthesis rates during solid-set sprinkler irrigation. This different wettability of alfalfa leaves may also have an influence on the reduction of alfalfa ET rates due to the irrigation as compared to the previously reported reductions of maize ET. Subsequently, the contribution of alfalfa ET reduction during and after sprinkler irrigation to application efficiency could be somewhat different to that reported for maize. Thus the general objective of this paper was to quantify the net sprinkler evaporation losses (SEL_n)

for the alfalfa crop and its components. This objective will be reached through the following specific objectives:

- Analysis of the meteorological (air temperature, relative humidity and vapor pressure deficit) and physiological changes (canopy temperature) in alfalfa during and after solid-set sprinkler irrigation.
- Characterization of the alfalfa ET before, during and after sprinkler irrigation as compared to that occurring at the same time in an alfalfa crop not being irrigated at that moment.
- Evaluation of the gross WDEL ($WDEL_g$) and estimation of the net WDEL ($WDEL_n$) when the contribution of the alfalfa ET reduction during and after irrigation is taken into account.
- Estimation and modeling of the net interception losses (IL_n) for alfalfa.
- Quantification and modeling of the sprinkler evaporation losses (SEL_n).

III.2. MATERIAL AND METHODS

III.2.1. General characteristics of the experiments

This research was conducted during the 2009 irrigation season (March-October) at a 2.0 ha field located in Montañana (Zaragoza, NE Spain). Geographical coordinates are 41°43′ N latitude and 0°49′ W longitude, and the elevation is 225 m above the sea level. The crop was alfalfa. The field was divided in two plots of 1.0 ha each, plots A and B. The available water holding capacity within the top 1.2 m of the soil profile in these plots was 0.173 m^3 m^{-3}. The soil is classified as *Typic Xerofluvent*, with a sandy loam texture, mixed (calcareous), and mesic (Soil Survey Staff, 1999).

The climate is semiarid Mediterranean. The mean annual values of several meteorological variables are: air temperature, 14°C (24.2 °C for July and 4.8 °C for December); precipitation, 340 mm; reference evapotranspiration (ET_o), 1,230 mm. The predominant wind directions are northwest (locally denominated Cierzo, dry and cold) and southeast (locally denominated Bochorno, dry and hot) with an annual average wind speed (2-m above ground level) of 2.3 m s^{-1}, classified as moderate wind (Martínez-Cob et al., 2010).

A solid-set sprinkler irrigation with a square spacing of 15 m x 15 m was installed in the 2 ha experimental plot (Figure III.1). Impact sprinklers (RC-130 model Riegos Costa, Lleida, Spain) were used. These sprinklers had nozzle diameters of 4.4 mm and 2.4 mm, a vertical throw angle of 25°, and the nozzle height was located at 2.2 m above the ground. Irrigation pressure was measured every 5 min during each irrigation event by two pressure transducers (Model 2200/2600, Gems Basingstoke, Hampshire, United Kingdom), one in each plot, located in the sprinkler riser pipe at 2.2 m above the ground (Figure III.1). The working pressure (P, kPa) measured by the transducers was used to calculate the gross irrigation depth (I_g, mm) using the following equation based on the Torricelli's Theorem and the Orifice Equation (Norman et al., 1990):

$$I_g = \frac{\left[0.00035\,\pi\,D_C\sqrt{P}\left(d_1^{\,2}+d_2^2\right)\right]\,t}{S} \tag{III.2}$$

where D_C is the discharge coefficient (D_C = 0.98 as determined experimentally by Playán et al., 2006); d_1, d_2 are the large and small nozzle diameter, respectively, mm; t is the irrigation event duration, s; and S is the area irrigated by one sprinkler, m^2 (in this experiment, equal to 15 m x 15 m= 225 m^2). The application rate for this sprinkler layout working at a pressure of 300 kPa was 7.5 mm h^{-1}. For the evaluated irrigations the rate varies according to the working pressure and the irrigation time.

Irrigations were scheduled to meet the crop water requirements, which were computed weekly from reference evapotranspiration (ET_o) estimates and local crop coefficients. Daily ET_o was computed using the FAO Penman-Monteith method (Allen et al., 1998) from the daily meteorological values (air temperature and relative humidity, wind speed and global solar radiation) recorded at a standard automatic weather station located at a grass plot ('grass weather station'), adjacent (northern side) to plot A. Local crop coefficients were derived from tabulated values (Allen et al., 1998) adapted according to local phenological and meteorological data (Martínez-Cob 2004). Weekly crop water requirements were converted to weekly crop irrigation requirements (NIR, mm) using the following expression:

$$\mathrm{N}IR = \frac{K_c\, ET_0 - EP}{EF_{apl}} \tag{III.3}$$

where EP was effective precipitation, mm, estimated as 75% of recorded precipitation (Dastane 1978); and EF_{apl} is water application efficiency estimated as 80% for the solid-set sprinkler irrigation (Clemmens and Dedrick 1994).

A weekly irrigation schedule was established according to NIR such that each plot was irrigated 2 or 3 times per week not exceeding 4 h per irrigation event (~30 mm per event) to avoid soil saturation. The irrigation was alternated between plots, so when a plot was irrigated (moist treatment, MT), the second plot was not irrigated (dry treatment, DT). However, both plots were fully irrigated covering the alfalfa water requirements, and both plots received approximately the same seasonal irrigation depth. Once one plot was irrigated, the other plot was irrigated approximately 8 hours later to ensure that the microclimate effects were totally removed (Cavero et al., 2009).

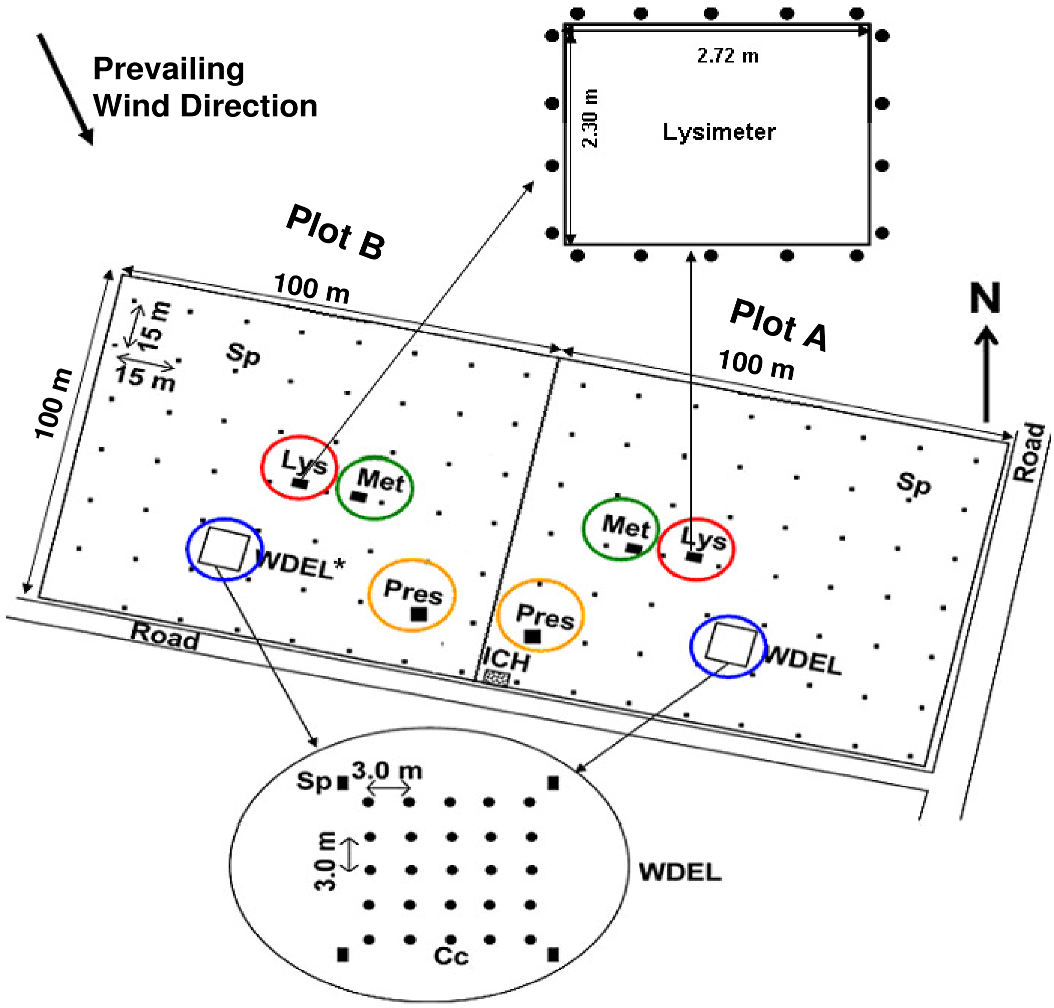

Figure III. 1. *Scheme of experimental plot: (WDEL$_g$) location of measurement of wind drift and evaporation losses and uniformity coefficient; (Lys) weighing lysimeters; (Met) automatic meteorological stations; (Pres) irrigation pressure transducers; (Sp) sprinklers; (ICH) irrigation control hut; (Cc) catch cans. Catch cans at 2.0 m height were located in plot B, at the same frame as catch cans at 0.85 m (WDEL).*

III.2.2. Water Loss and uniformity Calculations

Following ASAE.S.398.1 (1985), the sprinkler irrigation performance was evaluated by the gross WDEL (WDEL$_g$, %) and the uniformity coefficient of Christiansen (CU, %). These two variables were measured using a network of 25 plastic catch cans (at a spacing of 3 m X 3 m) that was arranged within four sprinklers in each plot (Figure III.1). Catch can (own manufacture) were conical in its lower part (100 mm length) and cylindrical in its upper part (200 mm length). The diameter of the upper part was 160 mm. The catch cans were marked in mm for direct readout up to 45 mm. Catch cans were placed at 0.4 m above the ground just after each alfalfa clipping and at 0.85 m once the alfalfa crop reached a full development to ensure the catch cans were always above the alfalfa canopy. WDEL$_g$ (%) was estimated as the percentage of water delivered by sprinklers (I$_g$, mm) and not collected within catch cans or collectors (I_{cc}, mm) (Dechmi et al., 2003; Playán et al., 2005; and Sánchez et al., 2010a). I_{cc} was the average of the water collected at the 25 catch cans.

$$WDEL_g = \frac{\left(I_g - I_{cc}\right)}{I_g} \times 100 \tag{III.4}$$

The coefficient of uniformity proposed by Christiansen (1942) was computed as:

$$CUC = 100 \times \left(1 - \frac{\sum_{i=1}^{i=25} \left| h_m - h_i \right|}{n \times h_m} \right) \tag{III.5}$$

Where:

n: Number of pluviometers.

h_m: Mean water depth collected.

h_i: Water depth collected in pluviometer i.

$\sum_{i=1}^{i=25} \left| h_m - h_i \right|$: Sum of the absolute values of the individual deviation from the mean of the water depth collected.

An additional network of 25 catch cans was installed at 2.0 m above ground only in plot B. Irrigation uniformity and WDELg comparison was made using the collected data at 0.85 m height [$CU_{0.85m}$ and $(WDELg)_{0.85m}$] with those collected at 2.0 m height [CU_{2m} and $(WDELg)_{2m}$]. The aim of this comparison was to characterize the CU and $WDEL_g$ in the field at different collector heights.

III.2.3. Reduction of evapotranspiration during irrigation

Alfalfa evapotranspiration at each subplot was measured by a weighing lysimeter located at the middle of each subplot (Figure III.1). Each lysimeter had an effective surface area of 6.26 m^2 (length 2.72 m x width 2.30 m, both measured up to the mid-point of the inner-outer wall). Lysimeter depth was 1.7 m. Both lysimeters were made of stainless steel with a thickness of 6 mm. A more detailed description of the lysimeters is presented in Martínez-Cob, (2001). Lysimeters recorded 5-min evapotranspiration (ET) rates that were composite into hourly totals from the 2 h before to the 3 h after each irrigation event. During the irrigation event, 5-min ET rates recorded at the dry treatment lysimeter (ET_{DT}) were summed and later converted to mm h^{-1}. However, it was impossible to directly measure ET rates during the irrigation event at the moist treatment lysimeter (ET_{MT}) due to its gain of mass because of the applied irrigation water. Thus, the ET_{MT} rates during the irrigation event were determined as follows (Martínez-Cob et al., 2008):

$$ET_{MT\_di} = \frac{I_{lcc} - I_{lys}}{t} \tag{III.6}$$

where: ET_{MT_di} is the estimated ET rate at the moist treatment during the irrigation event, mm h^{-1}; I_{lcc} is the water depth applied to the lysimeter during the irrigation event, mm; I_{lys} is the water depth recorded at the lysimeter during the irrigation event, mm; and t, duration of the irrigation event, h. I_{lcc} was determined as the average water depth collected in 18 catch cans (Figure III.1), similar to those used for measurement of $WDEL_g$, located just around the lysimeter, a few centimeters apart from the outer wall of the lysimeter tank. The I_{lys} was determined as the gain in mass by the lysimeter during the irrigation event divided by its effective surface area (Martínez-Cob, 2001). Uncertainty of Eqn. (5) arises from the different resolution of the catch cans and the lysimeter, about 0.5 and 0.05 mm, respectively.

Martínez-Cob et al., (2008) reported that maize ET reduced by about 32-55 % on average during irrigation events while maize transpiration reduced by about 58 % on average. This difference in the percent reduction of both variables was due to the evaporation of intercepted water at the soil and crop surfaces during the irrigation. In other words, the estimated values of ET_{MT_di} also include the evaporation of the intercepted water during the irrigation. For impact sprinklers, the magnitude of the evaporation of the intercepted water at the soil should be relatively negligible (Yonts, 2000) and the evaporation of the intercepted water at the crop surfaces will be also relatively small due to the reduction of VPD (Steiner et al., 1983a; Thompson et al., 1996; Schneider and Howell, 1995).

The ET rates of the different irrigation events at both moist and dry treatments were compared for the two periods (1 and 2 h) before, during, and three periods (1 to 3 h) after the irrigation events. A Student t-test for paired samples was performed to test the null hypothesis that the difference between averages ET at both treatments was equal to 0 (α = 0.05). The t-test was applied for each of the six abovementioned periods.

As previously mentioned, part of the $WDEL_g$ replaces crop ET during the irrigation events. Then, the work hypothesis is that the reduction of crop ET (i.e., the difference between ET_{DT} and ET_{MT} during the irrigation events) can be subtracted from $WDEL_g$ to get the net WDEL. Therefore:

$$WDEL_n = WDEL_g - \sum_{i=0}^{t}(ET_{DT} - ET_{MT})_{di} \tag{III.7}$$

Where: $WDEL_n$ are the net wind drift and evaporation losses, mm; t is the total irrigation duration, h; and $(ET_{DT}\text{-}ET_{MT})_{di}$ is the reduction of ET during the irrigation event (di), mmh^{-1}.

After the irrigation, the crop transpiration of the wetted surface continues to be reduced for some time (Martínez-Cob et al., 2008). But that reduction is less after irrigation than during the irrigation event (as it occurs for VPD reduction) so transpiration reduction is lower than the evaporation of intercepted water. Then, the difference between ET_{MT} and ET_{DT} after the irrigation should represent the net interception losses, i.e. the difference between the gross interception losses and the reduction of transpiration after the irrigation. Thus, after the irrigation event (ai), and during the time it takes for this water to evaporate, the following equation holds (Martínez-Cob et al., 2008):

$$IL_n = \sum_{i=0}^{m}(ET_{MT} - ET_{DT})_{ai} \tag{III.8}$$

where: IL_n are the net intercepted losses, mm; m is the time duration after irrigation used to calculate the IL_n, h. The time after irrigation (ai) considered for the IL_n calculation corresponded to the time needed to equal ET_{MT} and ET_{DT} (i.e. until the irrigated canopy was dry). Values of $WDEL_n$ and IL_n were used to determine SEL_n applying Eq. (1).

III.2.4. Prediction of net sprinkler evaporation losses

Statistical analyses of prediction equations of $WDEL_g$, IL_n and SEL_n as a function of several meteorological variables: VPD, wind speed (U), solar radiation (R_{sol}), and air temperature (T_{air}) were performed using the Statgraphics Plus software (version 5.0, Statistical Graphic Corp. 1994-2000). The equations were selected through a backward stepwise procedure accounting for their statistical indicators used to monitor and compare the selected equations (Dolado, 1999): the adjusted coefficient of determination (adjusted R^2), the mean square error (MSE), the coefficient of efficiency (E) defined by Wilcox et al., (1990), the similarity index (IS) (Willmott, 1981) and the root mean square error (RMSE). Two additional statistics were introduced to evaluate the predictive capability of the equations: the average magnitude of the relative error (AMRE, %) and the prediction level 25 (Pred [0.25]) (Dolado, 1999). The Pred [0.25] is the percentage of the estimated values differing from the measured value by less than 25% (Dalado, 1990 and Playán et al., 2005).

III.2.5. Microclimatic changes

An automatic weather station was installed in the center of each plot, next to the weighing lysimeters (Figure III.1). Each station had a datalogger (Campbell Scientific model CR10X, Shepshed, Loughborough, U.K.) monitoring an air temperature and relative humidity probe (Vaisala model HMP45AC, Helsinki, Finland) and an infrared thermometer (Apogee Instruments Inc., Roseville, CA, USA) at 0.1 Hz (10 s). The temperature and relative humidity probe was installed at 1.5 m above ground; its accuracy was ± 0.3°C for temperature and ± 3% for relative humidity. The infrared thermometer was located at 1.0 m above the crop canopy with an angle of 45º and was oriented towards the north; its accuracy is ± 0.3ºC. Averages of air temperature and relative humidity were computed for each 5-min period, and 30-min averages of canopy temperature were computed and stored in the Datalogger memory. VPD was computed for each 5-min period using the 5-min averages of air temperature and relative humidity as described by Allen et al., (1998).

Values of air temperature, VPD and canopy temperature at both treatments were compared for the periods before (1 and 2 h), during and after (1 to 3 h) the irrigation events. As for ET, the Student t-test for paired samples was used (Devore and Peck, 1986).

III.3. RESULTS AND DISCUSSION

III.3.1. General characteristics of the experiments

The total irrigation depth applied in the 2009 irrigation season for alfalfa was 798 mm and 813 mm for plots A and B, respectively. This slight difference was due to the slightly greater irrigation pressure in the plot B (308 kPa) than that in the plot A (302 kPa). The total number of irrigation events for the entire irrigation season was the same for both plots (42 events); minimum, maximum and average irrigation durations were 1.0 h, 4.0 h and 2.5 h, respectively.

A total of 24 daytime irrigation events (12 at plot A and 12 at plot B) and 12 nighttime irrigation events (6 at plot A and 6 at plot B) were evaluated for $WDEL_g$, microclimatic and ET changes before, during and after irrigation, $WDEL_n$ and SEL_n. Table III.1 summarizes the general characteristics of the evaluated irrigation events. The average applied irrigation water per event was 21.1 mm and 20.8 mm for daytime and nighttime irrigation, respectively.

Table III. 1. *General characteristics of the 36 evaluated irrigation events: irrigation events number (N), average irrigation time per event (IT, h), irrigation depth (mm), U (m s⁻¹) at 2 m above ground level, air temperature (ºC), vapor pressure deficit (kPa), $CU_{0.85m}$ (%), CU_{2m} (%), $(WDEL_g)_{0.85m}$ (%) and $(WDEL_g)_{2m}$ (%)Minimum and maximum values are between parentheses.*

Irrigation events	N	IT (h)	Irrigation Depth (mm)	U [(a)] ($m\ s^{-1}$)	T[(a)] (°C)	VPD[(a)] (kPa)	$CU_{0.85\ m}$ (%)	$CU_{2\ m}$ (%)	$(WDEL_g)_{0.85m}$ (%)	$(WDEL_g)_{2m}$ (%)
Daytime	24	2.7	21	2.5	24	1.47	83.5	79.4	11.6	15.1
		(1.8-4)	(14-31)	(0.6-5.8)	(16-32)	(0.52-4.36)	(66-91)	(64-90)	(0.8-27.5)	(0-36)
Nighttime	12	2.6	21	1.2	15	0.28	85.2	82	5	5.74
		(1.2-4)	(9-33)	(0.2-3.1)	(8-19)	(0.06-0.52)	(81-91)	(68-89)	(0-17.2)	(0-24.6)
Daytime and Nighttime	36	2.7	21	2	21	1.06	84	80.6	9.7	11.6
		(1.2-4)	(9-33)	(0.2-5.8)	(8-32)	(0.06-4.36)	(66-91)	(64-90)	(0-27.5)	(0-36)

(a) Recorded at the 'grass' weather station

Distinct general meteorological conditions occurred during daytime and nighttime irrigation events according to the recorded values at the 'grass station' (Table III.1). The average wind speed (U) during daytime irrigation (2.5 $m\ s^{-1}$) was twice that recorded during the nighttime events (1.2 $m\ s^{-1}$). The maximum wind speeds were 5.8 $m\ s^{-1}$ and 3.1 $m\ s^{-1}$ during daytime and nighttime irrigations, respectively. The mean air temperature and VPD were 24.4°C and 1.47 kPa, respectively, for daytime irrigations, while they were 14.8°C and 0.28 kPa, respectively, for nighttime irrigations.

The CU means were 84% and 80. 6%, at the 0.85 m catch can height and at the 2 m catch can height, respectively. A significant difference (α=0.05) was detected between the CU at different measurement heights. The CU differences (averaging 3.4 percentage units) can be explained by the differences in the intercepted height that affects the overlapping results. Same results were reported by Sánchez et al. (2010a) comparing CU values above maize with that above alfalfa obtained at the same time.

The mean values of $WDEL_g$ for all irrigation events were 9.7% and 11.6%, at the 0.85 m catch can height and at the 2 m catch can height, respectively, both located in the same experimental area (plot B Figure III.1). Several authors (Dechmi et al. 2003; Kincaid et al. 1996; Playán et al. 2005; Seginer et al. 1991a, b; Tarjuelo et al. 1994) pointed out that $WDEL_g$ increases principally with wind speed (U). Simple linear regressions between $WDEL_g$ and wind speed (U) were developed (Figure III.2a) for the two different measurements heights (0.85 m and 2 m). The coefficient of determination was slightly greater for the 2-m measurements than that for the 0.85-m measurements (0.86 vs 0.78, respectively). The $WDEL_g$ values for the 2m height measurements were systematically greater than those for the 0.85-m measurement height. The differences of $WDEL_g$ between the two catch can heights showed a significant (α= 0.05) relationship with wind speed (Figure III.2b). Differences in $WDEL_g$ remained moderate up to wind speeds around 2 m s^{-1}.Above that threshold, the overestimation of $WDEL_g$ measured at 2 m should be considered. The differences between $(WDEL_g)_{2m}$ and $(WDEL_g)_{0.85m}$ disagree with results from previous works that indicate an increment on $WDEL_g$ with the time of exposure (Burt et al. 1997; Lorenzini and De Wrachien 2005). For the same drop sizes, the trajectories reaching the 2 m high catch can were similar in shape and much shorter than the drop trajectories reaching the 0.85 m high catch can.

In summary, part of the drops intercepted at the 0.85 m catch can height was not intercepted at the 2 m catch can height, specially the small drops. The low horizontal velocity of the small drops (reported by Salvador et al. 2009 and Bautista et al. 2009) and the important number of small drops coming from the auxiliary nozzle that are located slightly below the principal one could partially explain the experimental differences.

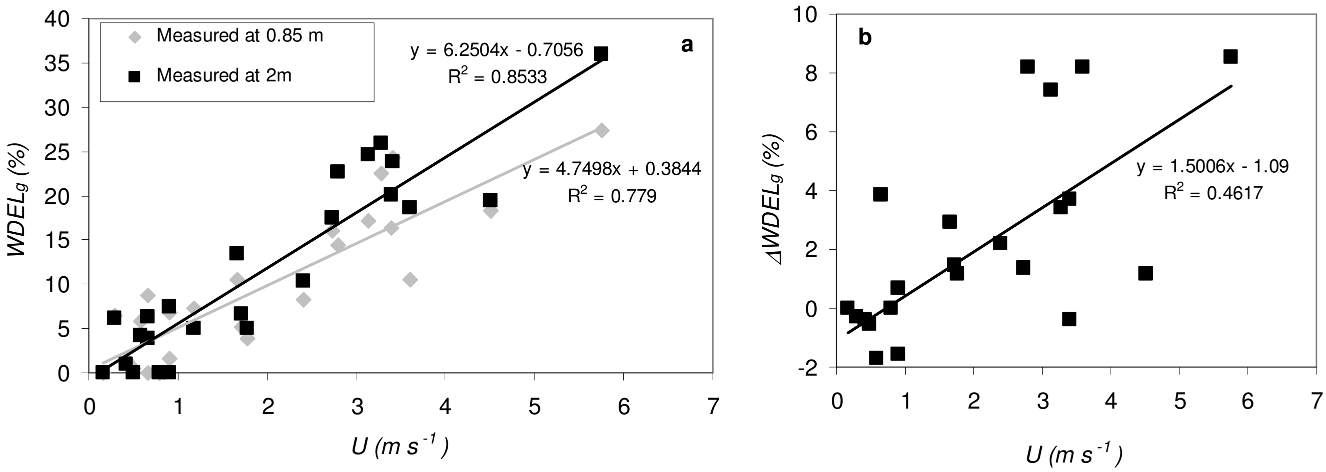

Figure III. 2. *Relationships between 2-m wind speed and $WDEL_g$ for the two catch can measurement heights are presented on Figure III.2a. Relationship between 2-m wind speed and the differences between $WDEL_g$ measured at the lowest height (0.85 m) and measured at the highest height (2 m) are presented in Figure III.2b.*

The experimental error identified for WDELg determination when using 2-m catch cans height in windy conditions can also introduce noise for the CU determination. With the experimental design differences on CU due to experimental drawbacks cannot be separated from differences due to overlapping. Sánchez et al. (2010b) measured the CU and the $WDEL_g$ above maize (at 2.25 m above ground level) and alfalfa (at 0.9 m a.g.l) crops and found that in windy conditions (U > 2.5 m s^{-1}), $WDEL_g$ at 2.25 m was notably greater, 17% and 28% for the alfalfa at 0.9 m and 2.25 m, respectively. As a result, given the shortening of the drops trajectories overlap because of a greater collector's height, CU resulted lower above maize. Playán et al., (2005) found that the height of the canopy determines the interception plane for the droplets emitted by the sprinkler, therefore, the trajectories overlap and the time that the drops remain in the air. In consequence, the irrigation uniformity and water losses should be affected by the sprinkler riser height.

III.3.2. Microclimatic and physiological changes during sprinkler irrigation

Microclimatic and physiological changes started immediately at the beginning of the irrigation events, more pronounced in the case of daytime events (Figure III.2). This agrees with the results reported by Tolk et al., (1995), Thompson et al., (1993b), and Cavero et al., (2009). During daytime irrigation events, a significant (α = 0.05) decrease in air temperature (T) was observed for the moist treatment regarding to the dry treatment (Figure III.3). On average, this temperature decrease due to sprinkler irrigation was 1.5°C. This decrease in temperature for the moist treatment remained significant (although less in magnitude, about 0.6°C, 0.1°C and 0.1°C on average for one, two and three hours after irrigation events respectively) until three hours after the end of the irrigation. During nighttime irrigation events, air temperature (T) of the moist treatment (MT) decreased also significantly (α = 0.05) as compared with the dry treatment (DT), but this decrease was much lower (0.4 °C on average) (Figure III.3).

Similar behavior was observed for the vapor pressure deficit (VPD) and the canopy temperature. The average decrease of VPD in the moist treatment during the irrigation was 0.44 kPa and 0.11 kPa for the daytime and nighttime irrigation events, respectively. The canopy temperature in the moist treatment declined 3°C on average during daytime irrigation events, although, that decrease was negligible during nighttime irrigation events (0.1ºC).

After the irrigation event, the difference in the VPD above the crop canopy between the non-irrigated plot (DT) and the irrigated plot (MT) were also significant (although at a lesser extent) until 2 hours after daytime irrigation and up to 3 hours after the nighttime irrigation.

The canopy temperature follows the same pattern as the VPD; a significant difference was also detected up to 3 h after daytime irrigation events. This difference was decreasing as time advance.

The decrease in air temperature, VPD and canopy temperature above alfalfa was less than reported by Cavero et al., (2009) 1.0 m above the maize canopy. The VPD was measured at 1.5 m above ground level which implies an average height of measurements above the alfalfa canopy of 0.7 m to 1.3 m. Differences in the meteorological conditions of the experiments, in the measurement height and in the density of both crops (maize and alfalfa) may partly explain the differences. Microclimatic and physiological changes lasted only 3 hours after irrigation at most. Other authors have also reported that microclimatic changes last for a short period of time after the irrigation (Cavero et al., 2009; Tolk et al., 1995).

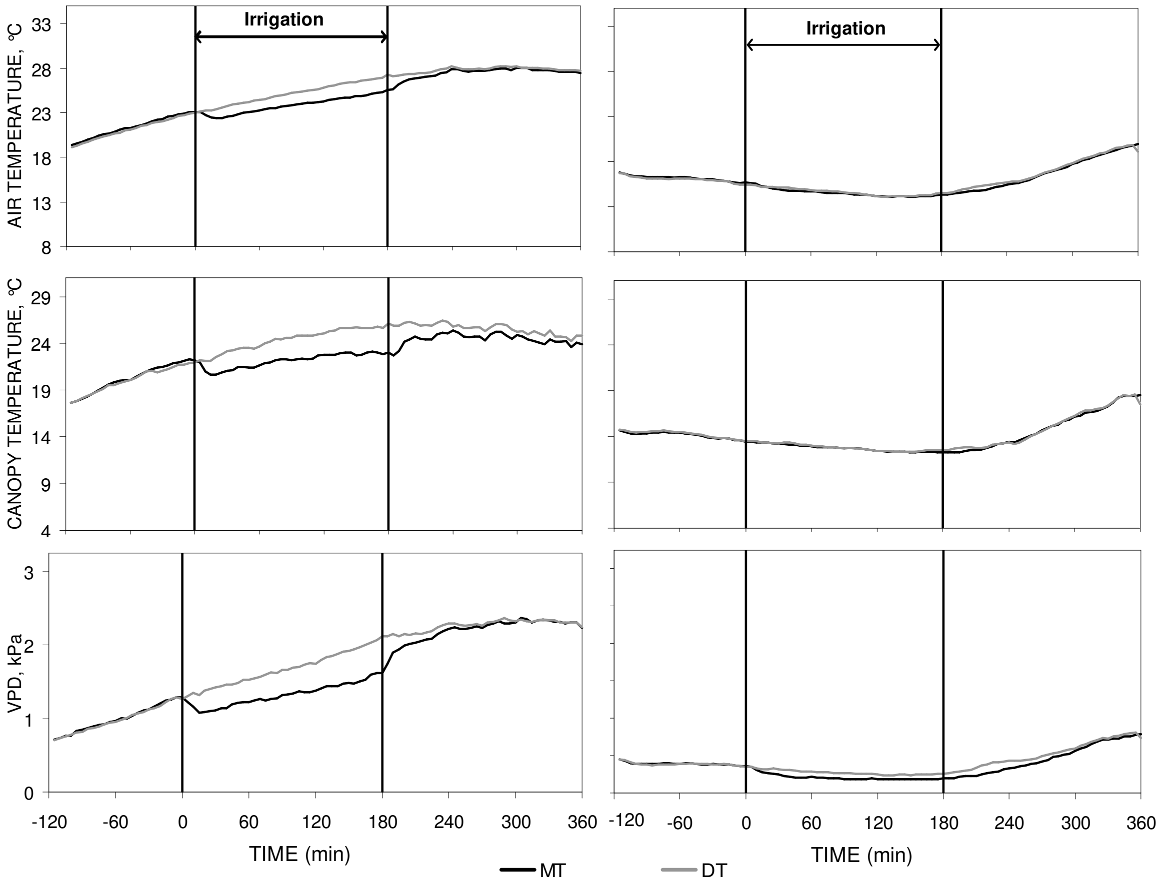

Figure III. 3. *Air temperature (T), Canopy temperature and Vapor pressure deficit (VPD) measured at the two treatments, moist (MT) and dry (DT), for 1-2 hours before, during and 1-3 hours after irrigation for daytime (left figure) and nighttime (right figure) irrigation events. Each value on the continuous line curves represents the average for all irrigations events lasting 3 hours.*

Figure III.4, shows the relationship between the 5 minutes averages of air temperature (T), alfalfa canopy temperature (TV) and VPD during the irrigation in the irrigated plot (MT) versus the corresponding averages recorded at the same time in the not irrigated plots (DT), for all evaluated irrigation events. Figure III.3 showed that microclimatic and physiological changes were more pronounced during daytime irrigation (Figure III.4 left) than during nighttime irrigation (Figure III.4 right). Cavero et al., (2009) reported the same patterns for corn and stated that the differences were due to the largest temperature and VPD conditions for the daytime irrigations.

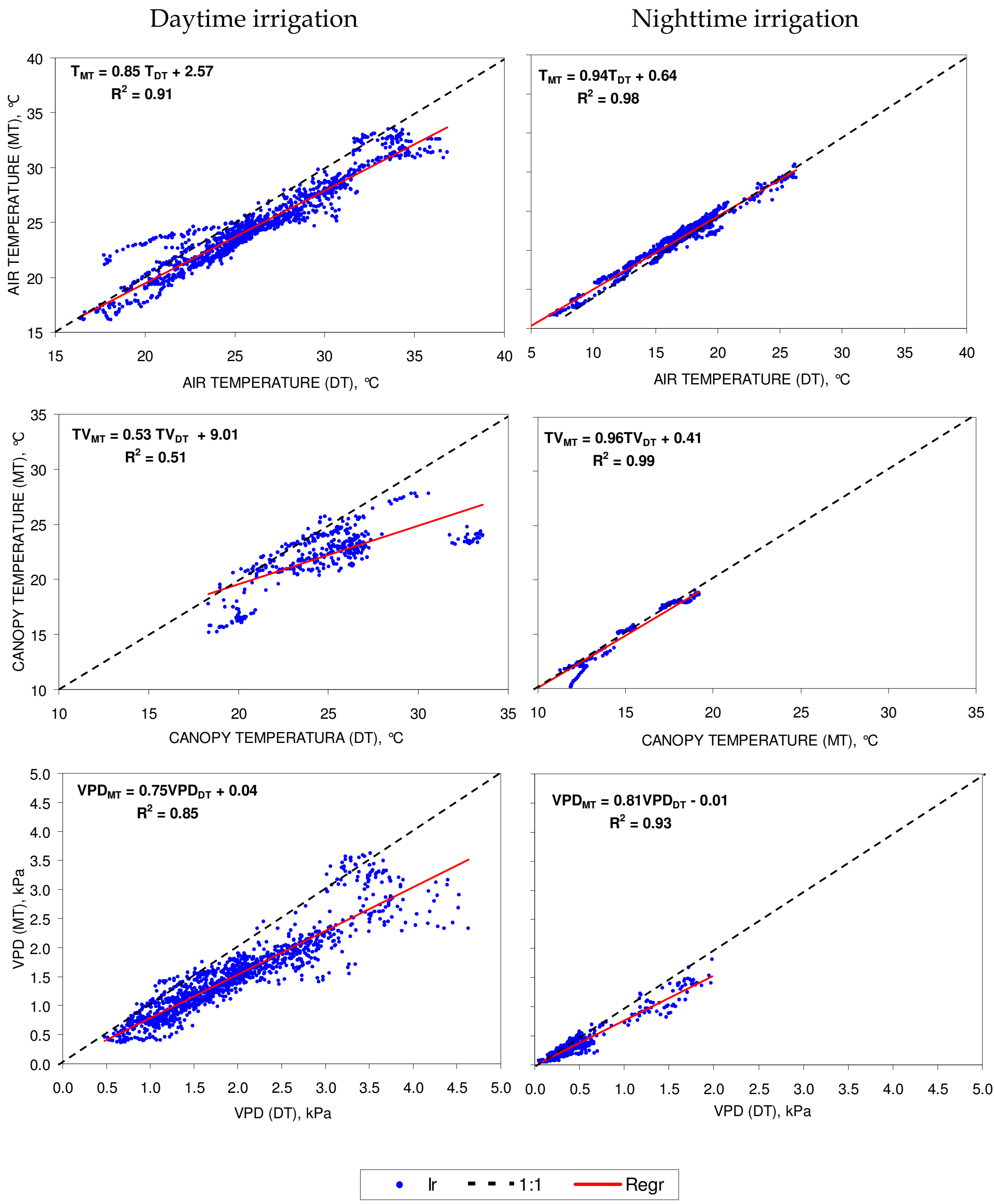

Figure III. 4. *5-min Air Temperature, Canopy Temperature and VPD values during daytime (left) and nighttime (right) sprinkler irrigation events at the moist treatment versus corresponding rates recorded at the dry treatment, regressions lines and equations were presented. Dashed lines correspond to the 1:1 lines.*

III.3.3. Sprinkler irrigation effects on crop evapotranspiration

Figure III.5 shows the average alfalfa ET rates for the moist treatment versus those for the dry treatment for the periods 1 and 2 h before, during, and 1 to 3 h after each daytime irrigation event. Likewise, the overall average values of ET_{MT} and ET_{DT} for alfalfa for the abovementioned periods are listed in Table III.2 for day and nighttime irrigation events. There was no significant difference (α = 0.05) between the two treatments 1 or 2 hours before the irrigation event for both daytime and nighttime irrigations (Figure III.5, Table III.2). However, ET_{MT} was significantly lower (about 42 % on average) than ET_{DT} during the daytime irrigation event (Table III.2; Figure III.4). This ET reduction in alfalfa (42%) was lower than that reported for maize (55 %) by Martínez-Cob et al., (2008) when these authors used the same approach to that used in this study (Eq. 5) to determine the ET_{MT}.

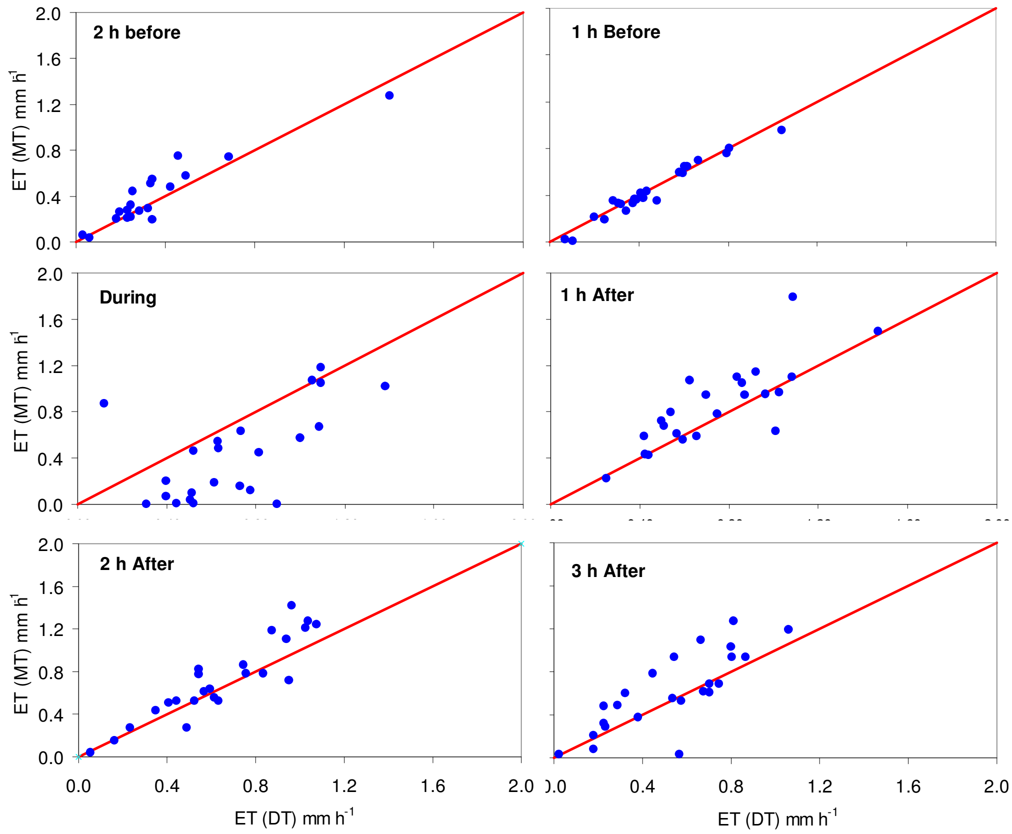

Figure III.5. *Average alfalfa evapotranspiration rates (ET) 1–2 h before, during, and 1–3 h after daytime sprinkler irrigation events at the moist treatment (MT) versus corresponding rates recorded at the dry treatment (DT).*

The differences on meteorological conditions between both experiments could partially explain the differences. For the alfalfa experiments the average air temperature (T), VPD and wind speed (U) were 24.4 °C, 1.47 kPa and 2.5 m s^{-1}, respectively, much lower than those reported by Martínez-Cob et al., (2008) for corn, 30.6 °C, 3.0 kPa and 3.0 m s^{-1}, respectively. Cavero et al., (2010) reported a reduction on the rate of photosynthesis for maize by 23% during the sprinkler irrigation event. However, photosynthesis of alfalfa was slightly increased (not significantly) during the sprinkler irrigation event. These authors reported difference in leaf characteristics (contact angle of water and canopies) between maize and alfalfa. This different wettability of alfalfa leaves may also have an influence on the reduction of alfalfa ET rates due to the irrigation as compared to the previously reported reductions of maize ET. Consequently, the contribution of alfalfa ET reduction during and after sprinkler irrigation to application efficiency could be somewhat different to that reported for maize.

Sternberg, (1967) used a weighing lysimeter to study rye grass ET during and after sprinkler irrigation events at Davis (California) and reported an almost complete suppression of ET during the irrigation and a reduction of about 33% after the irrigation. These different results can be attributed to the fact that Sternberg, (1967) used always the same lysimeter as moist treatment, while the lysimeter for dry treatment recorded systematically higher ET values before the irrigation. The results of this study have shown that ET was not completely suppressed during the irrigation because the transpiration, the main component of ET, decreased but was not suppressed (Martínez-Cob et al., 2008). During nighttime irrigation events, the differences between treatments were also statistically significant but the overall average values of ET for both treatments were small (Table III.2), within the precision of the lysimeter, so it could be assumed that the ET reduction during nighttime periods can be considered as negligible.

After the irrigation events, contrary to what was observed during irrigation, ET_{MT} was significantly (α = 0.05) greater (about 12.5 to 19 %) than ET_{DT} (Figure III.4, 1 h after and Table III.2). This increase of ET_{MT} after the irrigation event was due to the evaporation of canopy intercepted water and to the lower transpiration reduction between the dry and the moist plot compared to that occurring during the irrigation event (Figure III.4) (Tolk et al., 1995; Martínez-Cob et al., 2008). These highest ET rates for the moist treatment were only observed for the first hour after nighttime irrigation events, but for the three hours monitored after the daytime irrigation events. On average, the difference between ET_{MT} and ET_{DT} 1 to 3 h after daytime irrigations was quite similar (both in absolute and relative values), being this behavior somewhat different to that reported for maize by Tolk et al., (1995) and Martínez-Cob et al., (2008) for which the differences between treatments lasted no more than 1 to 2 h. This longer duration of the ET reduction after the irrigation was also likely due to the different meteorological conditions observed in this study (lower evaporative demand) and the earlier irrigation starting time that may affects the ET reduction (11:20 GMT in this study versus 14:00 GMT reported by Martínez-Cob et al., 2008).

Table III. 2. *Average total daytime and nighttime evapotranspiration of moist (ET_{MT}) and dry (ET_{DT}) treatments during 2009 irrigation season, and average differences ET_{DT} - ET_{MT} during, 1-2 hours before and 1-3 hours after the irrigation event.*

PERIOD		Daytime irrigation				Nighttime irrigation			
		N	ET_{DT} (mm h^{-1})	ET_{MT} (mm h^{-1})	ET_{DT}-ET_{MT} (mm h^{-1})	N	ET_{DT} (mm h^{-1})	ET_{MT} (mm h^{-1})	ET_{DT}-ET_{MT} (mm h^{-1})
Before	1 h	24	0.44	0.42	0.02^{ns}	12	0	0.01	-0.010^{ns}
	2 h	24	0.27	0.31	-0.04^{ns}	12	0.07	0.06	0.012^{ns}
During		24	0.7	0.41	0.29^{s}	12	0.01	-0.07	0.074^{s}
After	1 h	24	0.71	0.82	-0.11^{s}	12	0.17	0.24	-0.080^{s}
	2 h	24	0.64	0.72	-0.08^{s}	12	0.34	0.35	-0.009^{ns}
	3 h	24	0.52	0.62	-0.09^{s}	12	0.45	0.45	-0.002^{ns}

N=sample size; s=significantly different than 0 (a=0.05); ns=not significantly different than 0 (a=0.05); a= ET_{DT}-ET_{MT} = ($WDEL_g$-$WDEL_n$) Irrigation event duration (h); b= ET_{DT}-ET_{MT} =−ILn.*

III.3.4. Determination of net sprinkler evaporation losses

Table III.3 summarizes the applied water, the $WDEL_g$, the reduction of ET during irrigation event, and the balance of sprinkler evaporation losses for the daytime and irrigation events evaluated in this work. The gross irrigation water applied (I_g) for the 36 evaluated events was 757.4 mm, and the measured $WDEL_g$ was 64.6 mm, 8.5% of the total applied water. $WDEL_n$ for both daytime (6.6% of applied water) and nighttime (3.0% of applied water) irrigation events were smaller than $WDEL_g$ for those two periods, 10.9% and 3.7% of applied water, respectively, due to the contribution of ET reduction during the irrigation events. The ET reduction observed in this study for daytime irrigations was 21.6 mm (4.3 % of applied water), value slightly lower than the 4.8% reported for maize by Martínez-Cob et al., (2008). Nighttime ET reduction (0.8 % of applied water) was similar to that reported by Martínez-Cob et al., (2008). Total nighttime irrigated alfalfa ET is as much as 12 % of the total daily (24-h) alfalfa ET due to the lower VPD and U during nighttime periods (Tolk et al., 2006). For this reason, nighttime ET reduction was extremely low. However, the $WDEL_n$ reported by Martínez-Cob et al., (2008) were higher than those observed in this study. This was due to the higher $WDEL_g$ values reported by Martínez-Cob et al. (2008) for both daytime and nighttime irrigations; in this study, average daytime $WDEL_g$ was 10.9 % while it was 19 % in the research found by Martínez-Cob et al., (2008). The different average wind conditions for the two studies, 2.4 m s^{-1} in this study and 3.0 m s^{-1} in the study of Martínez-Cob et al., (2008), as well as differences in canopy height and architecture (Sánchez et al., 2010b) explained these different $WDEL_g$ values.

Net interception losses (IL_n) 1-3 h after the irrigation events were larger for daytime irrigation (15.9 mm, 3.1% of the daytime applied water) than for nighttime irrigation (6.0 mm, 2.4% of the nighttime applied water). When considering all the irrigation events, IL_n for alfalfa resulted in 2.9% of the total applied water, greater than the 1.1% IL_n reported by Martínez-Cob et al., (2008) for maize. Since IL_n includes water on leaf and stem surfaces and water trapped in the leaf sheath area, the variation in IL_n between crops can only be partially attributed to differences in crop architecture and characteristics of the leaf sheath of both crops. The higher IL_n value found in this work was mainly due to the fact that the differences on ET between dry and moist lysimeters remained significant until 3 hours after the irrigation for the daytime irrigation events of the alfalfa crop (Table III.2), i.e. more time than that reported for maize, likely due to the different meteorological conditions observed in this and the work of Martínez-Cob et al. (2008).

Table III. 3. *Gross wind drift and evaporation losses ($WDEL_g$), evapotranspiration reductions during irrigation ($(ET_{DT}$-$ET_{MT})_{di}$, net wind and evaporation losses ($WDEL_n$), net intercepted losses (IL_n) and net sprinkler losses (SEL_n) for the evaluated irrigation events.*

Irrigation Events		**N**	***I_g* (mm)**	***$WDEL_g$***		***$(ET_{DT}$-$ET_{MT})_{di}$***		***$WDEL_n$***		***IL_n***		***SEL_n***	
				(mm)	*(%)*	*(mm)*	*(%)*	*(mm)*	*(%)*	*(mm)*	*(%)*	*(mm)*	*(%)*
Daytime	Average	24	21.1	2.3	10.9	0.9	4.3	1.4	6.6	0.7	3.1	2.1	9.8
	Total		507.1	55.3		21.6		33.7		15.9		49.5	
Nighttime	Average	12	20.9	0.8	3.7	0.1	0.8	0.6	3.0	0.5	2.4	1.1	5.4
	Total		250.3	9.3		1.9		7.4		6.0		13.4	
All Irrigations	Average	36	21.0	1.8	8.5	0.7	3.1	1.1	5.4	0.6	2.9	1.8	8.3
	Total		757.4	64.6		23.5		41.1		21.9		62.9	

Adding IL_n to $WDEL_n$ resulted in SEL_n of 62.9 mm (8.3 % of applied water) when considering all the irrigation events (Table III.3). For daytime irrigations, SEL_n were 49.5 mm (9.8 % of applied water), while for nighttime irrigations, SEL_n were 13.4 mm (5.4 % of applied water) (Table III.3). The difference between $WDEL_g$ and SEL_n for daytime irrigation represented 1.1% of the total applied water, lower than reported by Martínez-Cob et al., (2008) for maize (1.8%), due to the higher wind speed and evaporative demand reported by these authors, also these differences would be partially explained by the differences in crops height and architecture between maize and alfalfa.

For nighttime irrigation events, the almost negligible reduction of ET rates added to the IL_n led to a higher average SEL_n value compared to the average $WDEL_g$ value, being the average difference between them of 1.7% of applied water. Similar results were found by Martínez-Cob et al., (2008) for maize nighttime irrigations (a difference of 1.5% of applied water between $WDEL_g$ and SEL_n). The $WDEL_g$ has been traditionally used in sprinkler irrigation engineering because of its experimental determination simplicity as an irrigation performance variable to characterize the adequacy of an irrigation event or schedule. However, the SEL_n represents a more adequate variable to characterize the sprinkler losses. The SEL_n values for daytime irrigation resulted slightly lower that the corresponding $WDEL_g$, indicating that the sprinkler application efficiency was slightly higher (1.1 % for alfalfa and 1.8 % for maize crop) than that could be derived using the traditional variable, $WDEL_g$. On the other hand, for nighttime irrigation events, SEL_n values resulted slightly higher that the corresponding $WDEL_g$, indicating that the sprinkler application efficiency was slightly lower (1.7 % for alfalfa and 1.5 % for maize) than that could be derived using the traditional variable, $WDEL_g$. These results should be taken into account in irrigation scheduling.

Figure III.6 shows the measured IL_n values for all irrigation events (daytime and nighttime) versus the average VPD recorded after the irrigation period. The selected equation presented in Figure III.5 was a linear regression model that describes the positive relationship between the independent variable VPD and IL_n. The increase in the evaporative demand of the air, due to the increase in VPD, will induce an important increase in the evaporation flux from the alfalfa intercepted water. This relationship established for alfalfa IL_n was not established for maize in Martinez-Cob et al., (2008). The different wettability of maize and alfalfa leaves can explain the different role of VPD on alfalfa and maize IL_n. A relatively moderate adjusted coefficient of determination was obtained for the IL_n equation (R^2_{adj}=0.47). The relationship depicted on Figure III.6 shows the best suited equation obtained by backward stepwise method to predict the IL_n according to its explicative and predictive capabilities and its statistical significance (α lower than 0.01). The mean absolute error (MAE) for this equation was very low, less than

0.001%, the coefficient of efficiency (E) and the Similarity Index (IS) were 0.65 and 0.89 respectively and very close to 1.0 presenting a better agreement between observed and predicted IL_n values. The Pred [0.25] indicates that the 45% of the predicted IL_n differing from the measured IL_n by less than 25%.

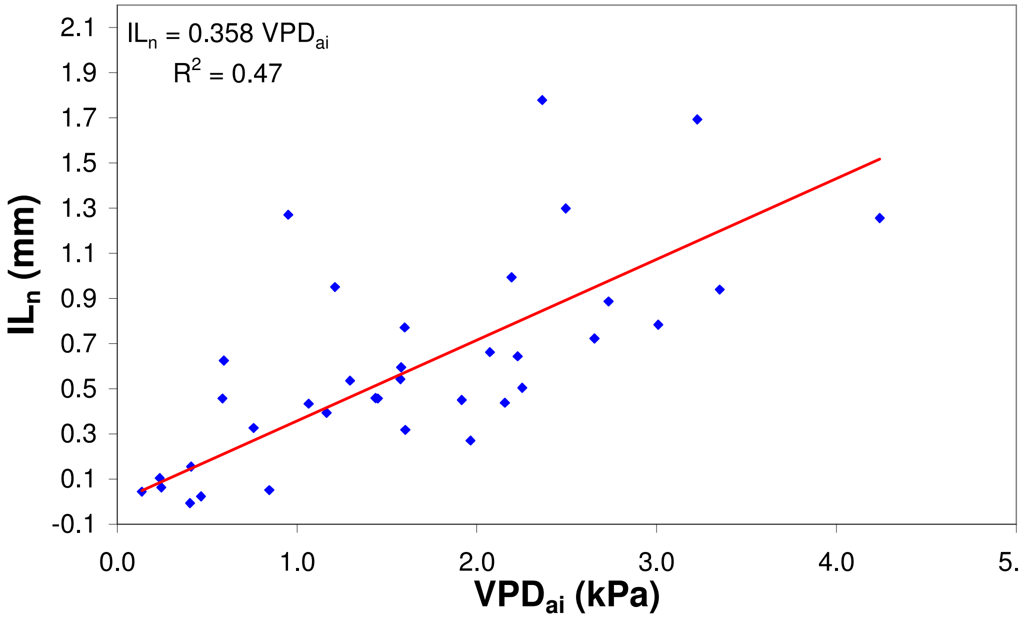

Figure III.6. *Net intercepted Losses (IL_n) calculated after all irrigation events (daytime and nighttime) versus the vapor pressure deficit (VPD). The IL_n were cumulative values until no difference between treatments was observed (1 to 3h after the irrigation event). The VPD was recorded at the 'grass station' and averaged for the same period of time.*

The best suited equation obtained to predict $WDEL_n$ uses the wind speed as the explicative variable (statistical significance α = 0.01) (Figure III.6). The wind speed meteor has been reported by other authors (Playán et al., 2005; Zapata et al., 2007; Sánchez et al., 2011) as the most significant variable affecting the $WDEL_g$. A relatively moderate adjusted coefficient of determination was obtained (R^2_{adj}=0.41).

Wind speed also resulted the only significant variable (α = 0.01) explaining the SELn variability (R^2_{adj}=0.44). MAE, IS, E and Pred[0.25] were 0.02, 0.81 and 0.48, 60% respectively. The relationship between SEL_n and U was also found by Martinez-Cob et al., (2008) for maize. For conditions similar to those of this study, the regression equation obtained for all irrigation events to predict SELn as a function of U would be recommended.

Although the relationship is significant between both $WDEL_n$ and U and between SEL_n and U, considerable variability in SEL_n and $WDEL_n$ for the same wind speed was shown in Figure III.7. This variability may be partially explained by the variability in other meteorological variables (such as T, RH, and VPD) that did not improve significantly the prediction equations and were excluded by the backward or stepwise statistical procedure.

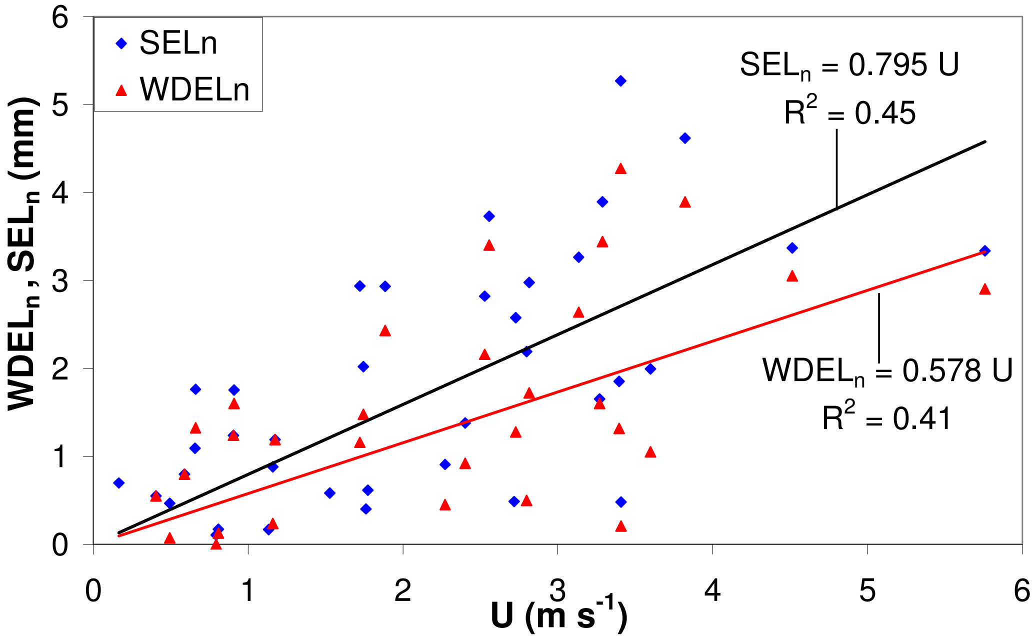

Figure III. 7. Net sprinkler evaporation losses (SEL_n) calculated for all irrigation events (daytime and nighttime) versus the wind speed (U). U was recorded at the 'grass station' and averaged for the periods during and after (1 to 3 h) the irrigation events.

Several researchers found that interception losses ranged from 1.8 to 2.7 mm for maize (Steiner et al., 1983b; Seginer, 1967; Smajstrla and Hanson, 1980; Lamm and Manges, 2000) and more than 10 mm for winter wheat under high evaporation condition (Du et al., 2001; Li and Rao, 2000). Tolk et al., (1995) found maize intercepted losses less than 8 % of the total water applied by impact sprinkler irrigation in day time, while Li and Rao (2000) found intercepted losses for winter wheat of 24–28 % of the total seasonal applied water. Thompson et al., (1993a, b) used a equation to calculate the net interception losses, which amounted less than 1 % of total applied water, less than the average IL_n (2.9 %) in this study. However, the uncertainty of the net interception losses estimated by the model of Thompson et al., (1993a) was relatively high. The differences in crops architecture and measurement methodologies complicate the comparison between results obtained from the literature.

III.4. CONCLUSIONS

Significant decreases of air temperature, VPD and canopy temperature were observed during daytime and nighttime sprinkler irrigations of alfalfa lasting up to 1 to 3 h after the irrigation events. Those decreases during daytime irrigation events were 1.5 °C, 0.44 kPa and 3.0 °C on average, respectively.

During the irrigation events there was a significant reduction of ET for the moist treatment compared to the dry treatment. The average reduction was much higher for daytime irrigation events (0.3 mm h^{-1}, 42 %) than for nighttime irrigation events (0.07 mm h^{-1}). Summing up all evaluated irrigation events, the daytime ET reduction amounted 21.6 mm (4.3 % of the applied water) and the nighttime ET reduction amounted 1.9 mm (0.8 % of the applied water). For 1 to 3 h after the daytime irrigation events, the ET at the moist treatment was greater (by about 12.5 to 19 % on average) than the ET at the dry treatment due to the combination of gross interception losses and reduced transpiration after the irrigation. Subsequently, the IL_n amounted to a total of 15.9 mm (3.1 % of the applied water) for all daytime irrigation events, and 6.0 mm (2.4 % of the applied water) for all nighttime irrigation events.

The $WDEL_g$ during daytime irrigation (10.9%) were greater than $WDEL_g$ during nighttime irrigation (3.7%) due to the different meteorological conditions. Discounting, the ET reduction and adding the IL_n, the SEL_n amounted a total of 49.5 mm (9.8 % of the applied water) for all daytime irrigation events, and 13.4 mm (5.4 % of the applied water) for all nighttime irrigation events. Subsequently the difference between the $WDEL_g$ and the SEL_n were modest, about 1.1 % and -1.7 % of the applied water for daytime and nighttime irrigation events, respectively. Therefore the contribution of reduced evapotranspiration during sprinkler irrigation events to the water application efficiency was modest.

An evaluation of predictive equations of SEL_n and its components, IL_n and $WDEL_n$ as a function of various meteorological variables (U, RH, T and VPD) was performed. The methodological characterization of SEL_n presented in this work was limited to the research field: for the $WDEL_n$ modeling, meteorological variables used were averaged on the period 'during the irrigation', while, for IL_n modeling, the meteorological values were averaged on the period 'after irrigation'.

The overestimation of $WDEL_g$ measured at 2 m above the ground, in conditions of moderate and high wind speed (U larger than 2 m s^{-1}), and was due to the lowest horizontal velocity reaching the catch cans of the small water droplets. These small drops have low possibilities to be intercepted by the taller catch can network.

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CAPITULO IV: IRRIGATION PATTERNS AND SCHEDULING OF A TELECONTROLLED IRRIGATION DISTRICT IN NORTH-EASTERN SPAIN

IRRIGATION PATTERNS AND SCHEDULING OF A TELECONTROLLED IRRIGATION DISTRICT IN NORTH-EASTERN SPAIN

RESUMEN

En los últimos diez años, la mayoría de los procesos de modernización de regadíos han incorporado sistemas de telecontrol a sus nuevas infraestructuras de riego. Estos sistemas abren muchas posibilidades en el campo de la gestión del agua de riego, sin embargo no existen herramientas que permitan explotar estos nuevos automatismos, relegando los sistemas de telecontrol a tareas rutinarias de control del funcionamiento de la red. La Comunidad de Regantes de Candasnos (CID) es una comunidad de riego presurizado equipada con un sistema de telecontrol. La CID se localiza en Aragón y dispone de 2344 ha de cobertura total, 1838 ha de pivotes y 414 ha de riego localizado. Los datos del telecontrol y los cálculos de las necesidades hídricas de los cultivos, nos han permitido analizar la calidad del riego en la CID para los cultivos mayoritarios (maíz, alfalfa y melocotonero) mediante el estudio de la evolución temporal del Índice Estacional de la Calidad de Riego (SIPI). Asimismo, se ha analizado la calidad del riego para los frutales de hueso y comparado a la estrategia de riego deficitario controlado (CDIR). Por otro lado, el seguimiento continuo de la presión mediante transductores de presión instalados en aspersores de los sistemas de riego de 10 parcelas de cobertura total permitió estudiar las pautas de riego utilizadas en las coberturas fijas de la CID. Los promedios de SIPI para el maíz, alfalfa y melocotonero fueron de 83%, 107% y 123%, respectivamente. Estos valores son indicativos de una eficiencia razonablemente buena en la zona regable. Los resultados del seguimiento del riego en parcela mostraron diferencias en el tiempo de riego por evento (1-1.5 h para el maíz y de 2-3 h para la alfalfa) y el intervalo entre riegos (más grande en la alfalfa que en maíz). Los riegos cortos y frecuentes detectados sobre todo para el cultivo de maíz pueden ser una causa de altas pérdidas por intercepción. Se encontraron dos pautas generales de manejo del riego en la CID: la primera se caracterizó por una mínima modificación del calendario de riego y la segunda se caracterizó por los cambios semanales en el calendario de riego. La segunda pauta es la más frecuente para los sistemas de cobertura fija. El análisis de los datos del telecontrol siguiendo esta metodología podría aplicarse fácilmente en la rutina diaria de la comunidad de regantes para mejorar la gestión del riego a nivel de parcela. Además, los datos del telecontrol pueden ser una herramienta importante para promoción y facilitación las estrategias de riego deficitario controlado en frutales de hueso.

PALABRAS CLAVE

Comunidad de regantes, calendario de riegos, sistema de telecontrol, pívot, cobertura fija, riego por aspersión, riego por goteo, riego deficitario controlado, índices de calidad del riego

ABSTRACT

Over the last ten years, telecontrol systems have been incorporated into the majority of modern collective pressurized irrigation networks in Spain. This type of infrastructure provides many opportunities for irrigation management but actually, in Spain, is only used for standardized network operations. The Candasnos irrigation district (CID), located in northeastern Spain, is equipped with this system, and contains a variety of different pressurized systems (2344 ha of solid-set, 1838 ha of pivots and 414 ha of drip irrigated plots). Telecontrol data and crop water requirements were used to analyze the evolution of irrigation performance (SIPI) of maize, alfalfa and stone fruits. Irrigation guidelines for stone fruit were analyzed and compared to those of standard and controlled deficit irrigation (CDIR) irrigation strategies. Ten solid set irrigation systems were monitored to determine on-farm irrigation patterns. The average SIPI of maize, alfalfa and peach was 83%, 107% and 123%, respectively. The average SIPI showed a high irrigation performance, however, the spatial and temporal variability of SIPI showed possibilities for improvement. Deficit irrigation practices were conducted on peach trees, but not adjusted to the recommended RDI strategy. The results of plot monitoring showed crop differences on irrigation time per event (1-1.5 h in maize and 2-3 h in alfalfa) and on time interval between irrigation (larger in alfalfa than in maize). The short and frequent irrigation timing for maize crop could be a disadvantageous practice since it yielded high evaporation losses from crop intercepted water. Two irrigation patterns were established at the CID: the first was characterized by structured irrigation schedules and the second was characterized by weekly changes in the irrigation schedule. The second pattern was more commonly employed in solid set systems than in those with pivots. The analysis of telecontrol data following this methodology could be easily implemented in the daily routines of the district office to improve irrigation management at the plot level. Further, telecontrol data can be an important tool for promoting and facilitating controlled deficit irrigation strategies in stone fruits.

KEY WORDS

Irrigation district; Irrigation scheduling; Telecontrol Irrigation System; Centre pivot; Solid set; Drip irrigation, Regulated deficit irrigation, irrigation performance indices.

ABBREVIATIONS

ADOR	= Irrigation district management software; Ador is a Spanish word derived from Arabic and means to turn (Pláyan et al. 2007)
ARIS	= Annual relative irrigation supply
CDI	= Controlled deficit irrigation
CID	= Candasnos irrigation district
CU	= Christiansen coefficient of uniformity
EP	= Effective precipitation
ET_0	= Reference evapotranspiration
ID	= Irrigation depth
Kc	= Crop coefficients
K_{rd}	= Reduction coefficient for controlled deficit irrigation
NCDIR	= Net controlled deficit irrigation requirements
NIR	= Net irrigation requirements
SIPI	= Seasonal irrigation performance index
VC	= Variation coefficient
WDEL	= Wind drift and evaporation losses

IV.1. INTRODUCTION

In the last decade, national and regional policies have encouraged the modernization of traditional irrigated land in Spain. The National Irrigation Plan was approved by the Spanish Government in 2002. This National Irrigation Plan allocated 61% of its total funds to the modernization of irrigation systems and infrastructures until 2008 (Forteza Del Rey, 2002). Current irrigation projects in Spain include the modernization of traditional irrigation systems and conversion to pressurized irrigation systems.

In Spain, the modernization of irrigation networks has been accompanied by the installation of modern telecontrol irrigation systems and has offered new methods for the control and management of irrigation systems. Telecontrol irrigation systems have become increasingly popular in Spanish irrigation districts and have provided water savings, improved crop productivity, optimized the use and timing of fertilizer applications and improved control of large irrigated land extensions (Damas et al., 2001). Control utilities have been rapidly incorporated in daily irrigation district management; however, real time irrigation management utilities have not been widely employed. Most irrigated land in Spain is supervised by user associations, which include thousands of individual plots with an average surface area of 1 ha (Damas et al., 2001). Telecontrol irrigation systems allow the centralized control of large regions of irrigated land (hundreds of control points and hydrants, thousands of hectares and inter-node distances of several kilometres) without the need to extend electricity to each hydrant. Moreover, installation and maintenance costs are minimized in centralized telecontrol irrigation systems (Damas et al., 2001). Moreover, telecontrol systems provide real-time water-use information on individual plots, allowing the analysis of irrigation performance and enabling personalized advising, which can improve water use at the plot level. However, the centralized control of different plots by user association agencies is rarely conducted in irrigation districts in Spain. Moreover, studies on the use of remote control and the supervision of on-farm irrigation management practices at the district level have not yet been conducted.

Irrigation performance is usually analyzed by determining a specific set of indicators (Molden and Gates 1990; Malano and Burton 2000; Playán and Mateos 2006). To conduct important assessments, the indicators should be locally adapted to describe the idiosyncrasies of the irrigated area (Lorite et al., 2004a). Due to the availability of water-use information at the individual plot, farmer or hydrant level, a meaningful assessment of irrigation performance can be conducted by determining the average performance indicators of the main crops in the area and assessing the variability among irrigation systems and farmers. If the average performance values are reasonable, then high variability among farmers indicates that irrigation management strategies can be improved (Fernandez et al., 2007). Telecontrol utilities offer continuous water use data at the hydrant level that can be used for this purpose.

Irrigation performance studies on seasonal on-farm water meter readings within irrigation districts have been performed for different irrigation schemes. For instance, Faci et al., (2000), Dechmi et al., (2003 a, b) and Lecina et al., (2005) analyzed the irrigation performance of sprinkler (the first two papers) and (the last paper) surface-irrigated districts in the Ebro Valley. Lorite et al., (2004 a, b) determined the variability among farmers and seasons in a sprinkler and drip-irrigated scheme in the Guadalquivir Valley. Fernandez et al., (2007) presented an on-farm irrigation performance analysis of three greenhouse irrigation schemes in southern Spain.

In the present study, irrigation patterns were evaluated using continuous water use data from the telecontrol irrigation system of the Candasnos irrigation district (CID) during 2009. Irrigation water use at the individual plot level was also evaluated and was compared to the crop irrigation requirements. Moreover, the potential uses of telecontrol data for the management of irrigation systems were explored. In addition, the current irrigation schedule at the CID and the variability among crops, irrigation systems and farmers were analyzed. Irrigation performance indices throughout the crop cycle of the main crops, an aspect that has not been sufficiently studied in the literature, were also evaluated in the present study. The CID was selected due to its diverse irrigation systems (solid set sprinkler irrigation, pivots and drip irrigation), the availability of telecontrol data and the variety of crops. The objectives of the present study were as follows:

1. Characterize the adequacy of irrigation application to crop irrigation requirements by analysing the temporal variability of the SIPI.
2. Characterize the irrigation patterns of different crops and irrigation systems (solid set, center pivot and drip irrigation) using telecontrol data.
3. Characterize on-farm block irrigation sequences of solid set sprinkler-irrigated plots by monitoring the hydraulic blocks.
4. Identify ways to improve water use in the district.

IV.2. MATERIAL AND METHODS

IV.2.1. The Candasnos Irrigation District

The Candasnos irrigation district (CID) belongs to the Riegos Del Alto Aragón irrigation scheme (Figure IV.1). The CID is located in the municipality of Candasnos (Huesca Province in the region of Aragón), and Aragón is located in the Ebro River Valley of north-eastern Spain. Aragón is an important agricultural production region and is equipped with modern irrigation systems. The main crops in Aragón are cereals, alfalfa and fruit trees. The CID covers a total area of 6,400 ha, of which 5,745 ha are irrigated lands. Irrigation water comes from the Canal de Sastago, which diverts water to a reservoir with a storage capacity of 210,000 m^3. The canal and reservoir are located 70 m above the highest topographical point of the irrigated land of the district. As a result, energy is not required to irrigate plots in the CID (the CID does not possess a pumping station). Sprinklers are the main irrigation system in the study region, and 73% of the irrigated area is sprinkler irrigated. 7% of the area is irrigated by drip irrigation and the remainder 20% was not equipped. Sprinkler irrigation systems in the study region are diverse, and a significant number of pivots (1,838 ha) and solid sets (2,344 ha) are employed. The quality of the irrigation water is high because it comes from melting ice in the Pyrenees' mountains of northern Spain.

Information about crop production for alfalfa and maize were provided by a local study based on farmer's interviews (CITA-CHE Unpublished data).

A soil sampling campaign was performed during the winter of 2009 to characterize the soil physical properties related to irrigation (soil holding capacity and texture). A total of 80 sampling points were selected covering the whole CID, and the soil was collected to a depth of 1.2 m or to the limiting depth. Samples were collected every 0.3 m, and the stoniness (percentage of coarse fragments > 2mm), texture, field capacity and wilting point of the soil were determined according to the methods of the Soil Survey Laboratory (2004). Volumetric stoniness (S, %) was determined for each soil sample from the weight of fractions above and below 2 mm, soil bulk density (ρ_b , Mg m-3) and the stone density. Soil bulk density and stone density were estimated as 1.40 and 2.65 Mg m^{-3}, respectively, in agreement with previous works in the area (Playán et al., 2000).

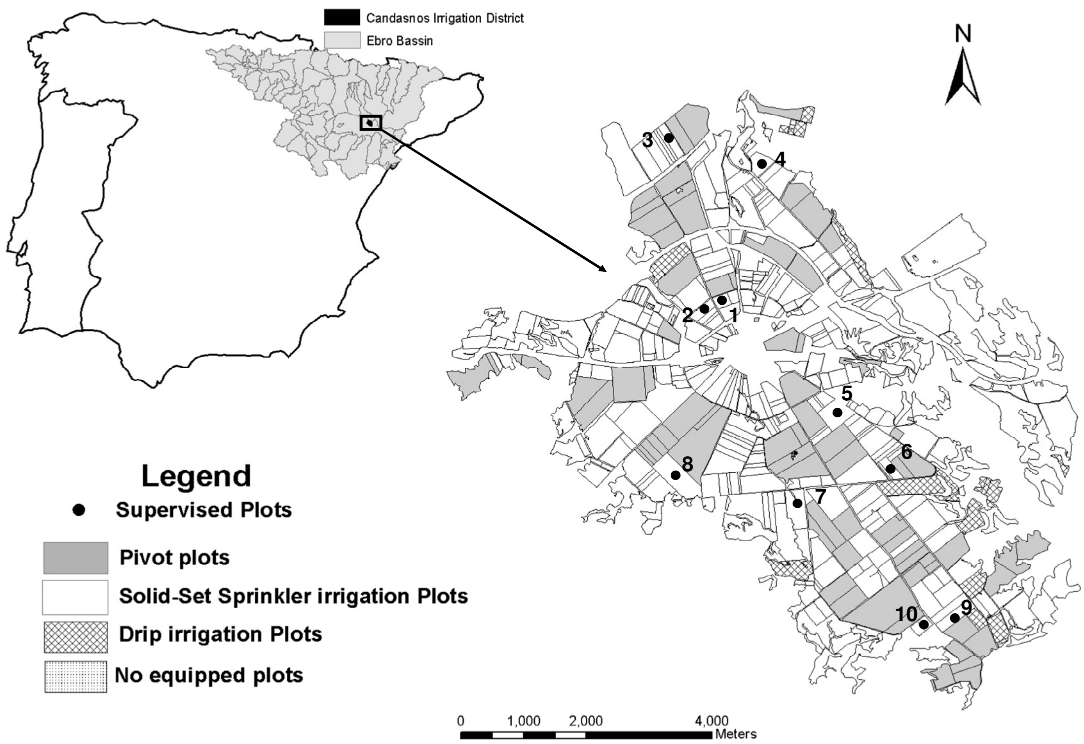


Figure IV. 1. *Location of the Candasnos irrigation district. Distribution of pressurized irrigation systems (pivots, solid-sets and drip) and location of the supervised plots.*

IV.2.2. The Seasonal Irrigation Performance Index of Maize, Alfalfa and Stone Fruits.

ADOR software (Playán et al. 2007) is currently used to manage the irrigation district in CID, and water delivery to farmers is conducted according to a previous water order scheme. This type of scheme is commonly used in surface irrigation systems and pressurized irrigation systems to control energy costs. Fortunately, energy costs are not a problem in the CID because irrigation water does not have to be pumped. Nevertheless, an advanced water orders scheme is used in the study region due to the low reservoir capacity. Moreover, the water must be ordered to the Ebro River Basin Agency two days before the water is released into the district. To apply irrigation, farmers must fill out a water order form by phone or directly in the district office, which includes the requested delivery date (a minimum of two days in advance), start time and total irrigation time.

The district files the water order and fits the order into the water delivery schedule. The ADOR network analysis module is used to determine if a water order can be physically delivered. Namely, the total water flow demand of the network in the CID is evaluated and it is verified that no over-exploitation of the irrigation network occurs. During the order confirmation process, the parameters of a water order can be altered by the district managers. Finally, the district verifies the water order and records the actual date, start time and volume of water applied to the field.

The irrigation network was provided with a telecontrol system (communicated by cable). The telecontrol system has been used by the district managers to perform the remote readings of the hydrant flow meters, to control incidences in the hydraulic network (breakdowns, opening and closing of the hydraulic valves); however, the system has not been used to analyze the water management standards. In 2009, the CID telecontrol system was modernized, and the communication software was upgraded to a more user friendly version. Since then, the telecontrol system remains underutilized by the district. The telecontrol system allows the water volume consumed by individual hydrants to be measured remotely; however, the district manager performs manual field readings of the water meters in the hydrants. Even if the hydrant is shared by several plots, the water consumed by each farmer can be adequately divided by the telecontrol data and the demand of the farmers. Currently, the telecontrol system is programmed to collect water volume data at each hydrant every six hours.

The irrigation network of the CID is composed of three manifolds (TPN1, TPN2 and TPNV) that act as independent networks. Each manifold has 3 or 4 irrigation control units that receive data from 18 to 72 hydrants (field units or remote units). During the present study, a communication error was detected in an irrigation unit in *TPN1* (corresponding to 31 hydrants and 802 ha). The problem was not detected by the district manager, indicating that the telecontrol data were underutilized by the district. The area without data was excluded from the monthly analysis; however, this area was included in the seasonal analysis because the final volume of water was obtained from the hydrant water meters by the manager (manually read).

The telecontrol data were used to calculate the volume of water applied to each plot throughout the crop cycle, and the results were compared to the net irrigation requirements (NIR). The NIR for each crop were considered equal for the entire irrigation district. The seasonal irrigation performance index (SIPI, Equation 1) was used to analyse irrigation performance in the CID. The SIPI (Faci et al., 2000) was defined as the ratio of the net irrigation requirement (NIR, Equation 2) to the volume of irrigation water supplied to the crops. The seasonal irrigation performance index is a simplification of the irrigation efficiency standard defined by Burt et al., (1997) and Clemmens and Burt (1997). Specifically, if a crop is water stressed, then the SIPI will be greater than 100%. Moreover, if the SIPI is greater than the application efficiency of the irrigation system, then the crop will be water stressed (Faci et al., 2000). The SIPI is commonly used as a seasonal parameter; however, in the present study, SIPI values were computed for short to seasonal crop periods to study the temporal variability of crop irrigation performance.

In 2009, monthly SIPI values for maize were calculated throughout the irrigation season to study water use in different phases of the crop cycle. For each plot of maize, the monthly cumulative SIPI was computed, and the results were spatially and temporally analyzed by GIS. To analyze the water use patterns of alfalfa, the SIPI of each cut was independently computed. Because the irrigation interval after a cut is usually longer than the regular irrigation interval, telecontrol data were used to determine the date of alfalfa cuts.

$$\text{SIPI} = \frac{\text{Net Irrigation Requirements (NIR)}}{\text{Irrigation Depth (ID)}} \qquad \text{(IV.1)}$$

Crop distribution in the CID varied from year to year, depending on the market demands. The crop cultivated in each plot of the CID during 2009 was obtained from the ADOR database. The crop distribution was spatially and numerically analyzed, and the reference evapotranspiration (ET_0) was calculated on a daily basis by applying the Penman-Monteith (Smith, 1993) method to the 2009 meteorological data.

The SIAR agro-meteorological station located in the Candasnos municipality (SIAR Candasnos) was used for meteorological data. The SIAR network of agro-meteorological stations was created in 1998 by the Spanish Ministry of Agriculture (MARM) (http://www.mapa.es/siar/Informacion.asp). This network covers most irrigated areas in Spain. Crop–water requirements for the 2009 irrigation season were computed from ET_0 estimates (following Penman- Monteith) and crop coefficients. NIR was determined using equation 2; ET_0 and EP were computed from the SIAR- Candasnos meteorological data. Values of K_c were estimated for maize using the thermal units methodology proposed by Martínez-Cob (2008). This methodology shows very good results compared with weighting lysimeters determination in the Ebro Valley region. For stone fruits values of Kc and Kc_{RDI} were established according to Martinez-Cob (2004) and Chalghaf (2008), respectively, for the same area of study. For alfalfa the methodology of FAO 56 was used to establish K_c values for each cut. Evett et al., (2000), illustrate that the FAO 56 methodology applied for alfalfa crop gives good result by comparison with lysimeters studies in a semi-arid area (Bushland, TX). For each alfalfa plot the cutting dates, number of cuts and irrigation dose were obtained by analyzing the telecontrol data. FAO 56 methodology was also used to establish Kc for winter cereals and other herbaceous crops.

For all of the studied crops, the net irrigation requirement (Equation IV.2) was obtained as the difference between crop evapotranspiration (ET_c) and effective precipitation (EP). Effective precipitation (EP) was calculated from the real precipitation according to the SCS method of the USDA (Cuenca 1989). EP is about the 75% of the precipitation recorded by the rain gauge (Martinez-Cob, 2004). For maize, monthly cumulative net irrigation requirements were established for May, Jun, July and August. For alfalfa, cumulative NIRs were obtained for each individual cut. Last, cumulative NIR were established for each FAO phase of stone fruit.

$$NIR = (Kc * ET_0) - EP \tag{IV.2}$$

The NIR was compared to the irrigation depth (ID) by determining the cumulated SIPI of different periods and crops. For stone fruits, the irrigation water supply, which was obtained from the telecontrol data, was compared to the standard net irrigation requirements (NIR, Equation IV.2) and to the net controlled deficit irrigation requirements (NCDIR, Equation 3). The NCDIR represents the minimum net irrigation requirement of fruit trees that maintains good vegetative development and does not affect the fruit quality or production of the orchard (Gelly et al., 2004). Cumulated SIPI values of the FAO crop phases for the two irrigation strategies (standard and controlled deficit) were calculated.

$$NCDIR = (Kc * Krd * ET_0) - EP \tag{IV.3}$$

Where *Krd* is the reduction coefficient of controlled deficit irrigation and is variable throughout the crop cycle (Chalghaf, 2008).

IV.2.3. Characterization of Irrigation Patterns

To identify differences between irrigation systems, the telecontrol data were also analyzed. Namely, for pivot irrigation systems, the total number of irrigation events, irrigation time per event and time interval between irrigations, seasonal irrigation depth and differences in irrigation schedules throughout the crop season were evaluated. The irrigation time was calculated as the duration of continuous hydrant operation, and the time interval between irrigations was computed as the non-operative hydrant time between two consecutive operations. The pivot rotation period was difficult to ascertain from the telecontrol data because most of the irrigation times represent several concatenated pivot cycles.

For solid set irrigation systems, the total number of irrigation events, irrigation time per event and time interval between irrigations, seasonal irrigation depth and differences in irrigation schedules throughout the crop season were determined. Differences in irrigation schedules throughout the crop season were analysed by comparing the irrigation time per event and the time between two consecutive irrigations in two different periods (from May to June and July to August).

Because a significant number of hydrants were operated in 2009 (290), several solid set (10) and pivot (15) hydrants were selected for further analysis. Pivots were selected to represent different crops, irrigation configurations (formation of a complete circle, semi-circle and ¾ of a circle) and irrigated areas. In addition, ten solid set hydrants were selected to represent different types of crops and irrigated areas. The irrigation schedule of solid set and center pivots for the same type of crop was compared.

The telecontrol data for drip irrigation were analyzed to determine the total irrigation time, irrigation time per event, and time interval between irrigations, seasonal irrigation depth and differences in irrigation schedules throughout the crop season. Four drip irrigation hydrants were selected to represent differences on plot and hydrant sizes. The four plots were managed by different farmers to analyze different irrigation management.

The telecontrol system of the CID provides data from hydrants that correspond to the farm level. Since the water flow of the hydrants were not enough to irrigate all the farm acreage at the same time with an adequate pressure, the irrigation system was divided in several irrigation blocks that irrigate sequentially. Since the telecontrol system rises to the hydrant level, the sequence of the irrigation blocks was unknown. Ten solid set plots (8 maize plots and 2 alfalfa plots) were monitored to determine the block irrigation sequence. A pressure logger (Dixon PR300) was installed in the middle of the sprinkler riser in a representative block of each monitored plot, and data were recorded every 15 min. The monitored block was similar to the other hydraulic blocks within the same plots with respect to the irrigation schedule. Data collected from the pressure logger were used to analyse the duration and number of irrigations, characterize daily and nightly irrigation, and determine the irrigation pressure throughout the irrigation season at the block scale. In addition, the pressure, nozzle size of the sprinklers, and the spacing and duration of each irrigation event were used to calculate the irrigation depth.

IV.3. RESULTS AND DISCUSSION

IV.3.1. The Candasnos Irrigation District

According to the 2009 ADOR database, the principal crops in the CID were maize (42.6%, 2445 ha) and alfalfa (20%, 1150 ha). Table IV.1 presents the area of each crop, number of hydrants and average seasonal irrigation depth of the crops during the 2009 irrigation season and SIPI. The third most common crop in the study region was stone fruits (7%), which corresponded to the total drip-irrigated area. Compared to neighbouring irrigation districts, a large area of the CID was devoted to maize during the 2009 irrigation season because the energy cost of irrigation was non-existent. In Spain and other developed countries, agriculture consumes large amounts of energy. For instance, in Spain, agricultural energy use accounts for 4.5% of the total energy use. In particular, the energy consumption of agricultural machinery and the application of irrigation accounts for approximately 70% of the total agricultural energy use (IDAE 2005). Because the input costs for maize production increase by nearly 50% due to cost of pumping water, the CID obtains a larger net margin for cropping maize (and other crops) than the neighboring irrigation districts.

Of the total area, 20% was not equipped with irrigation systems at the plot level. In Table IV.1, this area is referred to as no equipped. Alternatively, 2344 ha were equipped with solid set, 1838 ha with center pivots and 414 ha possessed drip irrigation systems. For most crops (except winter cereals), the variability in the irrigation depth (expressed as the variation coefficient in Table IV.1) between plots of the same crop was less than 30%. The extreme variability in the irrigation depth of wheat was due to the low number of wheat plots included in the study (3 plots). Also, Lorite et al., (2004b) studied an irrigation district located in southern Spain and demonstrated that rainfed crops (as wheat and barley) show high variability in the irrigation depth (67% to 130%).

The variability in the CID was lower than that of neighbouring districts such as the Montesnegros irrigation district, which presented variability values of 50% (Zapata et al., 2009), or the Loma de Quinto de Ebro irrigation district which displayed variability values between 30 and 40% (Dechmi et al., 2003a). The variability between plots was indicative of different hydrant capacities, number of irrigating blocks and farmer scheduling practices. The variability of irrigation depth, for the same crop, due to farmer scheduling indicated that irrigation water management practices in the CID can be improved substantially (Fernandez et al., 2007).

The alfalfa yield in the district varies from 10,500 kg ha^{-1} to 15,500 kg ha^{-1} with an average of 14,000 kg ha^{-1}. The maize yield varies from 11,000 kg ha^{-1} to 14,500 kg ha^{-1} with an average of 13,000 kg ha^{-1} (CITA-CHE, Unpublished data from 2009 irrigation season).

Soils in the CID showed spatial variability in the total available water (TAW) from a minimum of 42 mm (230 ha with a TAW between 42 to 60 mm) to a maximum of 275 mm (190 ha with TAW between 200 to 275 mm), with an average of 148 mm. These values of TAW did not present significant limitations for pressurized irrigation systems, which provide an important control on applied irrigation dose. The three main textural classes in the CID were loam, silt-clay-loam and silt-loam. All the soils were characterized by a low percentage of clay with respect to the silt percentage, medium texture and good infiltration. In general, soil texture did not affect sprinkler irrigation management.

Table IV. 1. *Summary of the telecontrol data for the 2009 irrigation season in CID.*

Crop	**Area (%)**	**Number of Hydrants**	**Average Seasonal Irrigation Depth* (mm)**	**SIPI (%)**
No equipped plots	20	81	-	-
Non cropped	4.7	29	-	-
Long cycle Maize	37.1	151	822 (22)	82 (18)
Short cycle Maize	5.5	31	660 (27)	92 (39)
Alfalfa	20	54	860 (17)	107 (28)
Stone fruits	6.7	29	565 (25)	123 (42)
Wheat	0.2	3	194 (120)	108 (92)
Barley	1.5	6	223 (37)	131 (57)
Double crops	2.9	6	928 (13)	89 (12)
Forage	1.1	8	826 (16)	79 (13)
Sunflower	0.3	2	519 (20)	110 (22)

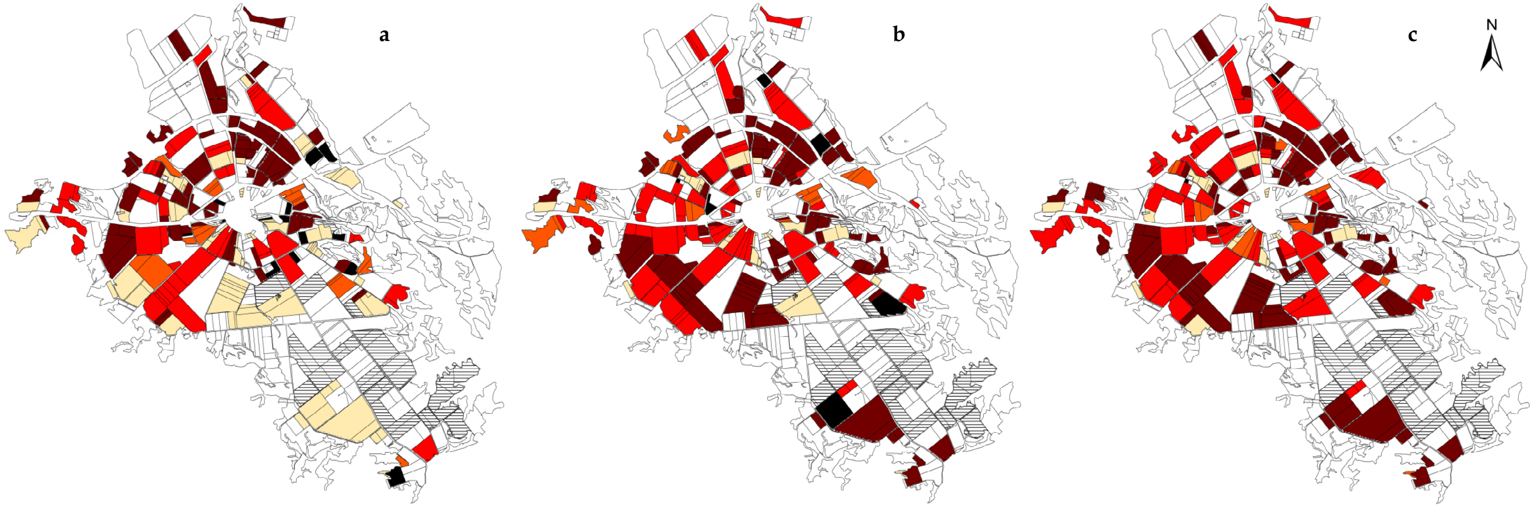
IV.3.2. The Seasonal Irrigation Performance Index for Maize, Alfalfa and Stone Fruits.

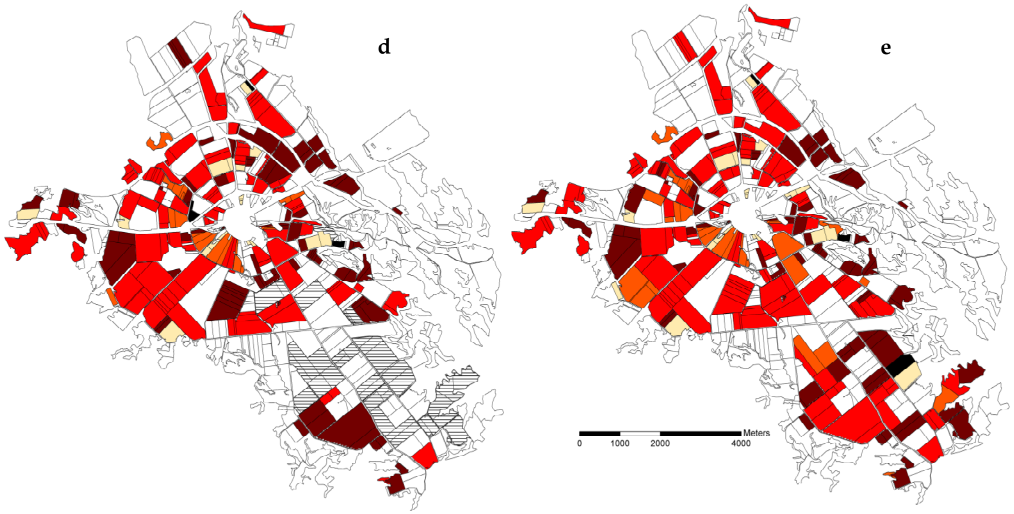
SIPI values for the 2009 irrigation season (Table IV.1) ranged from 79% (forage) to 131% (barley), and a crop seasonal average of 94% was observed in the CID. In general, the SIPI of stone fruits was greater than 100%, indicating that the application of deficit irrigation strategies is common in the CID. For winter cereals, the SIPI values were indicative of deficit irrigation practices. Alfalfa and maize presented average SIPI values of 107% and 83%, respectively, indicating that alfalfa was deficit irrigated and maize was adequately irrigated. These data suggest that farmers try to optimize water use by restricting application on drought resistant crops (sunflower and alfalfa) and limiting water stress on drought sensitive crops (maize).

The monthly evolution of the cumulative SIPI of maize in 2009 (Figure IV. 2) indicated that the proportion of maize plots with low SIPI values (<80%, over-irrigated) increased from the beginning of the crop season (May = 25.8% of the area) to July (40.5% of the area) and then decreased to 26.3% of the total area at the end of the season. As previously mentioned, telecontrol communication errors occurred on a remote unit of irrigation line TPN1. As a result, data for 19.2% of maize cropped area could not be obtained throughout the maize season (represented as no data in Figures IV.2a, IV.2b, IV.2c and IV.2d). Nevertheless, data on the seasonal irrigation depth of the total irrigated area were available because they were manually collected by the district manager.

Figure IV.2, shows the seasonal analysis of the SIPI of the entire maize-cropped area. For maize, light and frequent irrigations were applied in the early stages of crop development to promote germination and to avoid the formation of a crust on the soil surface, which is common in the study area. Excess water applied in June and July (41% of the analysed area presented a SIPI lower than 80%) was partially compensated by low irrigation levels in the final phases of plant growth. Namely, at the end of the irrigation season, 26% of the area presented a SIPI lower than 80% and 56% of the area presented a SIPI between 80% and 100%. Most of the over-irrigated plots at the end of the season (dark colored plots in Figure IV.2e) were attributed to persistent over-irrigation throughout the crop season (dark colored plots in Figures IV.2a, IV.2b, IV.2c and IV.2d). These plots would benefit from an advisory service based on telecontrol data analysis.

For alfalfa, the average SIPI was 107%, indicating that general deficit -irrigation was applied to this crop during the 2009 irrigation season. Table IV.2 presents the area of alfalfa according to the SIPI value. The analysis was performed for the entire season and each of the four individual cuts. The results indicated that 46.2% of the total area displayed a seasonal SIPI value greater than 100% (Table IV.2), suggesting that the supply of irrigation water was lower than the calculated irrigation requirements. Alternatively, 45.5% of the total area displayed a SIPI value between 80% and 100%, which is indicative of adequate irrigation management.





SIPI (%)	% Area				
	May	Jun.	Jul.	Ago.	Crop Season
< 50	2.7	5.9	0.1	0.5	1.0
50 - 80	23.1	34.8	40.4	29.5	25.3
80 - 100	18.4	27.2	30.5	41.6	56.0
100 - 120	5.6	4.5	3.9	4.0	11.2
>120	31.0	8.4	5.8	5.1	6.6
No Data	19.2	19.2	19.2	19.2	0.0

Figure IV.2. *Spatial distribution of the SIPI classes along the irrigation season for maize. Data are presented accumulated until (a) May, (b) Jun, (c) July (d) August and (e) the whole season. Table presents the percentage of area devoted to each SIPI class*

Only 8.3% of the total area presented a SIPI value less than 80%, which is indicative of over-irrigation. In general, the seasonal SIPI analysis revealed that the dose of applied irrigation was lower than the seasonal crop water requirements. Moreover, the SIPI values of individual cuts (Table IV.2) displayed an interesting pattern. Namely, for all of the individual cuts, the greatest proportion of alfalfa displayed SIPI values greater than 120% (accounting for 24% of the second cutting to 42% of the first cutting), which is indicative of deficit -irrigation. The high percentage of area that presented deficit irrigation strategies for the alfalfa crop was surprising. It has to be noted that the initial soil water content was not considered in the analysis and could introduce some noise, especially for the first and second alfalfa cuttings. In any case, a revision of alfalfa crop water requirements as proposed by FAO 56 to local conditions is suggested from these results.

Table IV.2. *SIPI values (%) of alfalfa computed for the four individual cuts and for the whole season.*

SIPI (%)	Area (%)				
	1st cut	2nd cut	3rd cut	4th cut	Seasonal
< 50	1.1	0.0	0.0	1.0	0.0
50 - 80	0.6	8.3	6.1	2.1	8.3
80 - 100	19.4	18.5	12.8	11.3	45.5
100 - 120	6.9	19.6	17.2	16.8	36.2
> 120	42.2	23.7	34.0	38.9	10.0
No Data	29.9	29.9	29.9	29.9	0.0

Although there are not available crop yields data associated to irrigation dose and schedule at farm level, the large variability of irrigation dose and the adequate average yield of the principal crops in the district, indicate an important potential for improvement of water use.

Figure IV.3 shows the weekly evolution of the applied irrigation depth, net irrigation requirements (NIR) and net controlled deficit irrigation requirements (NCDIR) for four medium cycle peach plots. The studied plots were selected by their differences in size and management (different farmer). In the four plots, the amount of applied irrigation was lower than the standard NIR throughout almost all of the irrigation season. The two plots presented in the upper portion of Figure IV.3 (IV.3a and IV.3b which correspond to hydrants VH097 and VH100, respectively) indicated that deficit irrigation strategies were applied until harvest (beginning of August). However, after harvest, a standard irrigation strategy was applied. Alternatively, the two plots in the lower portion of Figure IV.3 (IV.3c and IV.3d, which correspond to hydrants 1H141 and 1H139) indicated that deficit irrigation strategies were conducted throughout the entire irrigation season. Table IV.3 presents the SIPI of standard irrigation strategies, irrigation depth and the SIPI of controlled deficit irrigation strategies for 16 hydrants used to irrigate medium cycle peaches. The data are presented according to the four FAO phases. The average difference between the standard NIR and the applied irrigation depth for medium maturing peaches was approximately 15% - 27%.

However, for both standard and deficit irrigation strategies, extremely high SIPI values were observed during the initial crop development phase. Telecontrol data were analyzed from May onward and most probably the orchards were irrigated in March and April (data not available), also the initial soil water content was not considered in the analysis. Namely, hydrants 2H138, 1H059, 1H080 and VH058 corresponded to recently planted orchards; thus, the extremely high standard and controlled deficit SIPI values were attributed to low irrigation doses on young orchards. Except for VH097 and VH100 (Figure IV.3a and IV.3b, respectively), the remaining hydrants displayed standard SIPI values greater than 100%, which suggested that deficit irrigation strategies were performed on medium cycle peaches at the CID. Seasonal SIPI values of plots irrigated according to the CDI strategy were approximately 100% (except for VH097 and VH100) or higher, indicating that the total applied irrigation was similar or lower to the NCDIR. However, based on the SIPI values of the four FAO phases, the current irrigation strategy was not in accordance with the CDI strategy. Specifically, irrigation water reductions remained constant throughout peach development (sustained deficit), and the CDI strategy recommends water reductions at specific phases of the crop cycle. According to Gelly et al., (2004), the recommended phases of CDI are pit hardening (stage II of fruit growth) and postharvest. When the same amount of water is applied, the CDI is superior to sustained deficit irrigation in peach production (Fereres and Soriano, 2007). The CDI technique is based on the diverse sensitivity of the plant to water stress during different phenological crop stages. Intermittent water deficits during specific periods can increase the efficiency of irrigation, which saves irrigation water and improves harvest quality (Chalmers et al., 1981; McCarthy et al., 2002; Loveys et al., 2004; Cameron et al., 2006). Again, telecontrol data continuous analysis can be an important tool for promoting and facilitating CDI strategies in stone fruits.

Table IV.3. *Cumulated Irrigation depth (mm), Standard SIPI (%) and Regulated Deficit SIPI (%) according to the four FAO phases (Pini, Pdevelop, Pgrowing and Pfinal) for the 16 medium cycle peach hydrants. The SIPI for each crop phase was computed with cumulated data.*

Hydrants	Irrigation depth (mm)				Standard SIPI (%)				CD SIPI (%)			
	Pini	Pdevelop.	Pgrowing	Pfinal	Pini	Pdevelop	Pgrowing	Pfinal	Pini	Pdevelop	Pgrowing	Pfinal
1H141	6	27	351	513	691	304	136	129	691	256	114	106
1H142	4	23	286	533	1055	359	166	125	1055	303	140	102
2H138	0	0	223	363			213	183			180	150
1H059	7	17	270	314	617	505	177	211	617	425	149	173
1H128	5	28	386	484	786	298	123	137	786	251	104	112
1H133	8	33	383	564	528	253	124	118	528	213	105	96
1H137	4	20	273	521	1003	425	175	127	1003	358	147	104
1H139	3	21	349	504	1179	400	137	132	1179	338	115	108
VH056	10	38	389	548	389	219	122	121	389	184	103	99
VH090	6	27	293	505	680	314	163	131	680	265	137	107
VH097	9	35	379	665	451	239	126	100	451	202	106	82
VH100	10	40	434	622	418	208	110	107	418	176	93	87
1H138	5	22	292	435	853	375	163	153	853	316	138	125
VH089	6	25	321	558	647	329	149	119	647	277	125	97
1H080	4	17	113	113	1003	484	420	585	1003	408	354	479
VH058	3	11	159	203	1542	764	300	327	1542	644	253	267

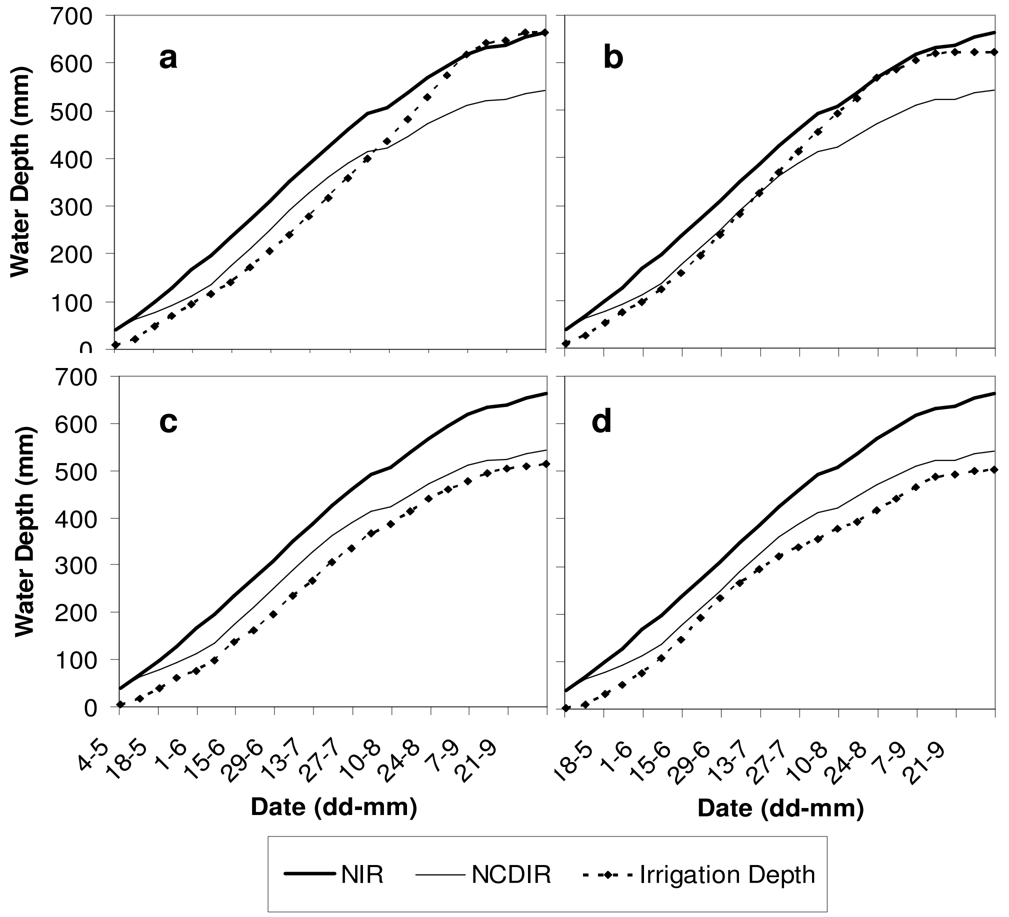


Figure IV. 3. *Weekly evolution of cumulated irrigation water, standard crop irrigation requirements (NIR) and regulated deficit irrigation requirements (NRDIR) for four plots of medium cycle peach (VH097, CH100, 1H141 and 1H139).*

Within irrigated areas in Spain, Faci et al., (2000) found that the Almudevar irrigation district in the Ebro Basin (surface irrigation) presented an average SIPI of 70%, which is indicative of over-irrigation. Alternatively, Stambouli, (2008) found that an irrigated area within the Las Filadas gully watershed (Huesca, Spain) possessed an average SIPI of 97.2% (similar to the average SIPI of the present study), which indicated that good irrigation management practices were conducted. However, sensible crops such as maize and rice were over-irrigated (SIPI values of 77% and 68%, respectively), and resistant crops such as barley and sunflower (SIPI values of 111% and 172%, respectively) were deficit -irrigated. In contrast, Dechmi et al., (2003a) studied another sprinklers irrigation district in the Ebro Valley region and found that the average SIPI value of the crops was 127% (indicative of deficit -irrigation). Lorite et al., (2004 a, b) determined the ARIS ratio (annual volume of irrigation water inflow/annual volume of crop irrigation demand) of the *Genil Cabra irrigation scheme* (southern Spain) and demonstrated that the average ARIS of the total area was less than 1 (from 0.45 in 1996-1997 to 0.64 in 1998-1999), indicating that irrigation applications did not meet the maximum ET demand. In general, average ARIS values for different irrigation areas around the world (Kloezen and Garcés 1998; Molden et al., 1998; Burt and Styles 1999) are higher than those obtained by Lorite et al., (2004a). This discrepancy was attributed to crop variability, irrigation methods, socio-economic conditions and the definition of ARIS, which varies slightly from author to author.

IV.3.3. Characterization of Irrigation Patterns.

In the CID 1,838 ha were irrigated by pivots. The minimum, maximum and mean pivot sizes in the CID were 4 ha, 80 ha and 22 ha, respectively; thus, high variability in pivot sizes was observed (VC = 63%). Major crops irrigated by central pivots include maize, alfalfa and double crops, which cover 1,080 ha, 573 ha and 64 ha, respectively. Fifteen representative pivots were selected to study the irrigation patterns of pivot irrigation systems in the CID. The studied pivots summarize the variability in crop, size, inflow rate and shape of the district pivots.

Table IV.4 presents the crop, hydrant denomination, irrigated area, pivot diameter, flow, irrigation time (h ha^{-1} $event^{-1}$) and interval between irrigation events of the selected pivots. The last two variables were computed for two periods (from May to June and July to August). For comparative purposes, the irrigation time was expressed in hour per hectare and event. Because the irrigation time and the water flow differs between pivot points, the irrigation time presented in Table IV.4 represents the average irrigation time per hectare at identical water flow rates.

Differences in irrigation time per event among plots of the same crop were typically accompanied by differences in intervals between irrigation events. In general, the irrigation time per event was greater for alfalfa than maize (from 1.27 to 15.63 h ha^{-1} $event^{-1}$ for alfalfa and from 0.42 to 6.78 h ha^{-1} $event^{-1}$ for maize). Moreover, the time between irrigations was larger for alfalfa. Most of the pivots irrigated several concatenated cycles between July and August, as indicated by the high irrigation time per hectare and event (Table IV.4). In general, the irrigation time increased from May-June to July-August. For hydrant 2H148 cropped with maize the irrigation time and the interval between irrigations remain constant throughout the irrigation season, indicating that the farmer did not modify the irrigation schedule. For hydrants 2H106 and 2H094, the irrigation time remained constant throughout the crop cycle; however, the interval between irrigations decreased from May-June to July-August. Figure IV.4 presents the change in the irrigation time in hours per hectare and event, and the change in the irrigation interval throughout the crop cycle. Figures IV.4a and IV.4b correspond to hydrants 1H003 and VH017, respectively, cropped by alfalfa. Figures IV.4c and IV.4d correspond to hydrants 1H069 and 2H018, respectively, cropped by maize.

Alfalfa pivot VH017 irrigated continuously from July to August and was only stopped to perform the cuttings (8.6 days in the cutting period, on average, Figure IV.4b and Table IV.4). Pivot 1H069, which was cropped with maize, followed the same irrigation pattern (Figure IV.4c). In this case, the low hydrant flow related to the size of the plot, forced the hydrant to irrigate almost continuously from July to August (the period of maximum irrigation requirements for maize). Even then, the irrigation dose (533 mm) was relatively low compared to the net water requirements for maize (648 mm). Alfalfa hydrant 1H003 (Figure IV.4a) showed four large irrigation intervals (from 9 to 15 days) corresponding to the dates between cuts. The irrigation time also varied throughout the alfalfa season, indicating that the farmer frequently modified the irrigation schedule.

Maize hydrant 2H018 (Figure IV.4d) presented an irrigation pattern consisting of light (1 to 1.5 hours of irrigation per hectare and event) and frequent (an irrigation interval of 1.5 to 2.5 days) irrigations from the beginning of the season to the end of June. The light irrigation change to continuous irrigation (15 to 43 hours of irrigation per hectare and event) between the beginning of July to the middle of August. With maize pivots, most farmers apply light and frequent irrigations until the end of June to avoid crust formation. Alternatively, from the middle of July to the middle of August, the pivot was operated almost continuously for 10 to 15 days (depending on the relationship between the size of the pivot and the hydrant flow). From the middle of August to the middle of September, light and frequent irrigations were again applied (Figures IV.4c and IV.4d). Thus, the results indicated that the analysis of pivot irrigation cycles could be used to better understand irrigation management strategies with sprinkler irrigation systems. In future studies, pivot movement should be monitored by GPS to establish pivot irrigation cycles.

Table IV.4. *Summary of irrigation scheduling for representative pivots: crop, plot size, diameter, inflow rate, irrigation time and days between irrigations for May to June and from July to August. Irrigation time and time between irrigation presented in this table corresponds to the most common values for the time considered, excluding the occasional extremes.*

Crop	Hydrant	Total Area (ha)	Inflow rate ($l\ s^{-1}$)	Seasonal Irrigation Time (h)	Irrigation Time May-June ($h\ ha^{-1}\ event^{-1}$)	Irrigation Time July-Aug ($h\ ha^{-1}\ event^{-1}$)	Time Between Irrigations May-June (days)	Time Between Irrigations July-Aug. (days)	Irrigation Depth (mm)
Maize	2H064	55.9	75	1381	0.50	1.00	1.00	0.70	668
Alfalfa	1H003	53.4	65	1493	3.37	2.97	4.50	4.30	675
Maize	2H148	46.4	62	1343	1.50	1.50	0.50	0.90	646
Maize	2H106	45.5	65	1295	0.85	0.86	1.40	0.50	667
Maize	1H069	35.5	23	1781	1.00	8.00	2.50	9.00	533
Maize	2H094	34.9	50	1472	1.15	1.13	1.37	0.52	760
Maize	1H019	30.6	45	1514	1.71	2.90	0.86	1.20	777
Maize	1H076	22.5	28	2067	3.01	4.63	2.89	1.12	772
Maize	1H145	20.9	23	1833	2.39	1.77	1.51	0.62	701
Maize	2H055	42.5	65	1566	0.70	2.92	1.61	1.55	704
Alfalfa	VH017	15.4	22	1781	2.40	15.63	1.65	8.62	860
Maize	2H018	11.9	16	1412	1.44	6.78	0.66	1.18	665
Maize	2H062	63.2	95	1652	0.42	0.70	1.00	0.75	897
Alfalfa	1H121	39.6	50	1665	1.27	2.62	0.40	0.48	774
Alfalfa	2H113	38.2	50	1281	1.79	2.40	1.92	1.96	628

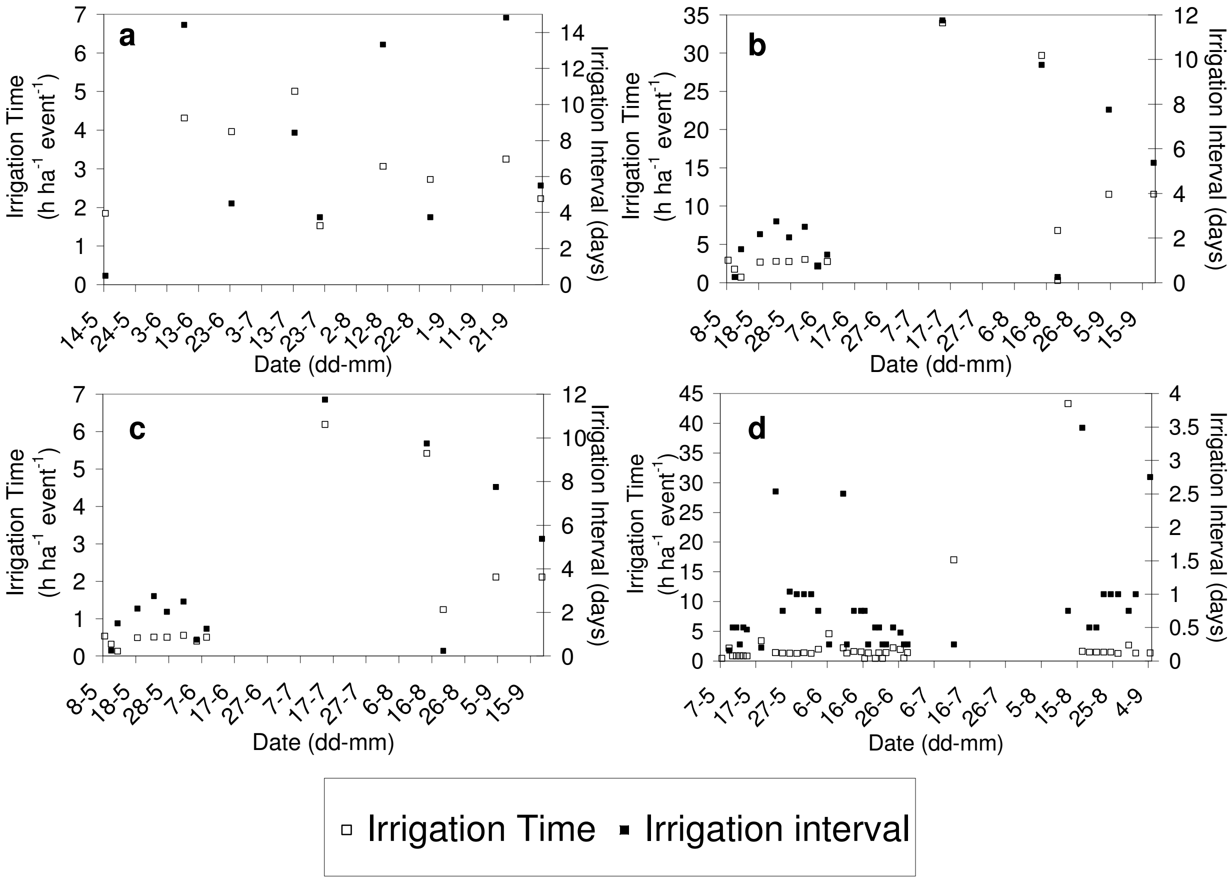


Figure IV. 4. *Evolution of the irrigation time (per hectare and event in hours) and the interval between irrigation (in days) during the irrigation season, for two alfalfa pivots (Figures IV.4a, 1H003, and 4b, VH017) and two maize pivots (4c, 1H069 and 4d, 2H018).*

The solid set was the most common sprinkler irrigation system in the study region (Figure IV.1). The mean area of solid set plots was 7.5 ha with high variability (VC = 120%). The most common sprinkler layout in the CID was triangular. In this configuration, sprinklers are placed in a straight line at 18-m intervals, and the distance between the lines is set to 18 m (T18x18). In the majority of the plots, the sprinklers were equipped with 4.8 mm and 2.4 mm diameter nozzles.

Table IV.5 presents the telecontrol data analysis of eight of the ten supervised plots (telecontrol data for the other two supervised plots, 1H092 and 1H108, were not available during the season). Moreover, the seasonal irrigation time (hours), seasonal irrigation depth, average irrigation time (expressed in hours per hectare and event) and the mean time between two consecutive irrigations during two representative periods of maize development (May-June and July-August) are also presented in Table IV.5. For the analysed crops (alfalfa and maize), the irrigation time increased during July and August, and the irrigation interval decreased with respect to the first period (May-June). Moreover, the irrigation depth of alfalfa was greater than that of maize. Namely, hydrants 2H043 and 1H062B, which were cropped by alfalfa, presented an irrigation depth of 1350 mm and 867 mm, respectively. In addition, the alfalfa plots presented the largest seasonal irrigation time (1924 hours and 1957 hours). For hydrant 2H043, the irrigation depth was excessively large compared to the alfalfa irrigation requirements for the 2009 irrigation season (843 mm). In most cases, time between irrigation in the second period were less than one day, which indicated that the capacity of the irrigation network to manage water in the presence of restrictions such as wind was relatively low.

Table IV. 5. *Telecontrol data analysis for eight of the ten supervised plots. Seasonal irrigation time, Irrigation time per hectare and event for two representative periods of crop development (May-June and July-August) and interval between irrigation in days for the same two periods. . Irrigation time and time between irrigation presented in this table corresponds to the most common values for the time considered, excluding the occasional extremes.*

Hydrant	Seasonal Irrigation Time (h)	Irrigation Time May-June (h ha^{-1} $event^{-1}$)	Irrigation Time July-Aug (h ha^{-1} $event^{-1}$)	Time Between Irrigations May-June (days)	Time Between Irrigations July-Aug. (days)	Irrigation Depth (mm)
1H014	1311	2.7	5	0.5	0.9	769
2H043	1924	1.8	2.2	1	0.33	1350
1H002	1706	0.7	2.1	0.8	0.7	778
VH012	1615	1.2	1.25	0.85	0.5	694
1H062B	1957	1.6	3.7	1.6	1.6	867
2H124	1028	0.6	0.75	1.1	0.66	626
2H100	1532	1	1.25	0.66	0.25	699
2H158	1380	2.34	2.77	0.5	0.5	780

Figure IV.5 presents the irrigation time and irrigation interval of four solid set hydrants throughout the irrigation season. The upper region of Figures IV.5a and IV.5b correspond to alfalfa solid set plots (hydrants 2H043 and 1H062B, respectively), and the lower portion of Figures IV.5c and IV.5d correspond to maize solid set plots (hydrants VH012 and 2H158, respectively). Hydrant 2H043 showed a nearly constant irrigation time of 1.8 hours per hectare and event in the beginning of the crop season; however, the irrigation time of hydrant 2H043 increased to 2.2 h ha-1 event-1 in July and August.

The relatively constant irrigation times were suddenly interrupted by abrupt applications of 10 or 18 hours per hectare and event at the beginning of June and the middle of July. For alfalfa, the irrigation interval was nearly constant at 0.25 days and was only interrupted by 4 to 12–day intervals, which corresponded to the alfalfa cuts. A continuous pattern was also observed for maize (hydrant VH012), as shown in Figure IV.5c. Specifically, the irrigation time was nearly constant at 1.2 hours per hectare and event throughout the entire maize cycle, except for the beginning of July and the beginning of August. During these time frames, the irrigation time increased to 12 or 25 hours per hectare and event, respectively. The irrigation interval from the middle of June to the end of the maize irrigation season remained constant at 0.33 days. Nevertheless, on some dates, 2 or 3 day intervals between irrigations were observed (probably after insecticide treatment).

The results shown in Figures IV.5a and IV.5c revealed that the farmer did not frequently alter the irrigation schedule. Alternatively, Figures IV.5b and IV.5d indicated that the farmer continuously modified the irrigation schedule throughout the crop cycle. For instance, as shown in Figure IV.5b, a continuous variation in the irrigation time per hectare was observed from the end of May to the beginning of August. Specifically, the irrigation time was increased by 2 to 6 hour increments per hectare and event. Finally, two 14 and 12-hour irrigations were performed in August. The irrigation interval presented a more consistent pattern than the irrigation time and was usually less than one day. However, 6 to 12-day intervals were also observed due to the alfalfa cuttings. Figure IV.5d shows the variability in the irrigation pattern of short cycle maize. Significant variability in the irrigation time was observed until the end of August, where the irrigation time increased from 1 to 7 hours per hectare and event. From the end of August to the end of the maize irrigation season, the irrigation time remained constant at 1 hour per hectare and event. Alternatively, from the beginning of July to the end of the season, the irrigation interval was equal to 0.5 days.

Irrigation times of 10 or 25 hours per hectare and event were obtained from the telecontrol data of the analysed hydrants (Figure IV.5). This was a surprising result because soil cannot handle such high irrigation doses. The irrigation data obtained from the pressure transducer installed at the supervised plots clarified these extremely high irrigation times. Table IV.6 presents the irrigation pressure and irrigation time obtained from the pressure transducer data. Hydrant 2H043 presented a constant irrigation time of 1.9 hour per hydraulic block and event throughout the entire alfalfa cycle, without regard to the abrupt increase in irrigation time (Figure IV.5a). Thus, when the block sequential irrigation cycles were concatenated, the hydrant counter did not stop, and the irrigation time was accumulated by the telecontrol system. The irrigation time measured by the pressure transducer at the nozzle of one block was the same as the irrigation time of the telecontrol data; however, a series of irrigations (2 hours) and cessations (22 hours to irrigate the others eleven blocks) were observed. The discrepancy between the telecontrol and pressure transducer data of hydrant 2H043 was also observed in the other analyzed hydrants (differences between Table IV.5 and Table IV.6). Moreover, the differences in the irrigation patterns between plots obtained from the telecontrol data analysis were significantly larger than that of the pressure transducer data. In addition, significant differences between the telecontrol and pressure transducer data were observed for hydrant 1H014. The pressure transducer showed a constant irrigation time of 1 hour throughout the maize cycle (Table IV.6), whereas the telecontrol data showed an irrigation time of almost 3 hours from May-June and 5 hours from July-August (Table IV.5).

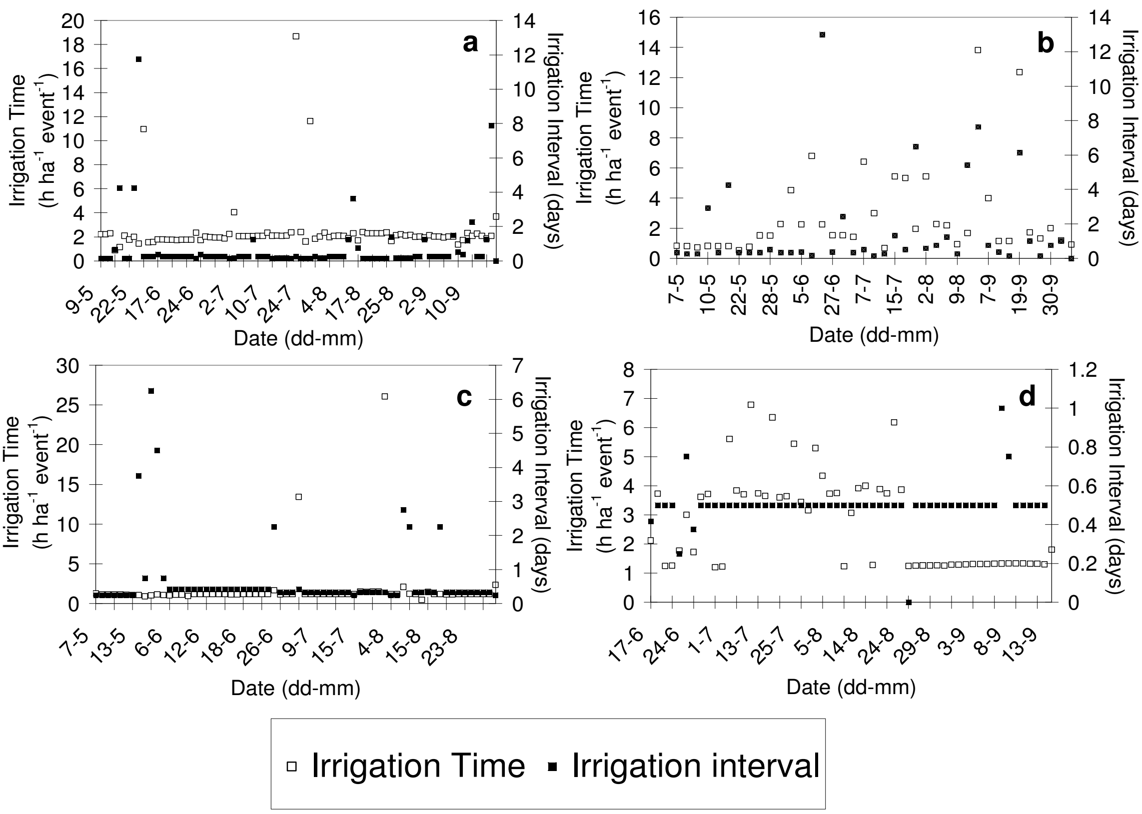


Figure IV.5. *Evolution of the irrigation time (per hectare and event in hours) and the interval between irrigation (in days) during the irrigation season, for two alfalfa solid set (Figures IV.5a and IV.5b, corresponding to hydrants 2H043 and 1H062B, respectively) and two maize solid set (Figures IV.5c and IV.5d,corresponding to hydrants VH012 and 2H158, respectively).*

Again, the concatenation of block sequential irrigation cycles showed a different irrigation pattern. Differences in irrigation management are important because short and frequent sprinkler irrigation (as shown in the ten supervised plots) yield high evaporation losses from crop intercepted water (independent of irrigation time, Wang et al., 2006; Mauch et al., 2008). However, short and frequent irrigation applications can be an alternative for problematic soils. The soils in the study region did not present significant water retention and runoff problems; thus, irrigation management could be improved by increasing the irrigation time per block and event.

Table IV.6. *Pressure transducer data analysis for the ten supervised plots. For each plot the crop, area, inflow rate, average and variation coefficient of irrigation pressure, average and variation coefficient of irrigation time per block and event and percentage of daily irrigation time were presented.*

Hydrant	Crop	Area (ha)	Inflow Rate ($l\ s^{-1}$)	Pressure* (kPa)	Irrigation Time* ($h\ block^{-1}\ event^{-1}$)	Daily Irrigation Time (%)
1H014	Long cycle maize	7.5	10	438 (3)	0.95 (16)	50
2H043	Alfalfa	9.3	12	389 (1)	1.91 (36)	51
1H002	Long cycle maize	20.3	26	243 (4)	1.35 (33)	84
VH012	Long cycle maize	13.5	16	356 (2)	1.11 (31)	16
1H062B	Alfalfa	18	22	328 (4)	2.86 (17)	34
1H092	Long cycle maize	11.9	15	254 (3)	1.28 (44)	42
2H124	Short cycle maize	26.6	32	318 (3)	1.47 (34)	20
2H100	Long cycle maize	16	20	411 (3)	1.27 (29)	77
2H158	Short cycle maize	9	16	346 (4)	1.48 (33)	8
1H108	Long cycle maize	30.8	37	321 (5)	1.58 (42)	55

**Average and Variation Coefficient (%)*

The low variability of the pressure at the nozzle point (the variation coefficient was less than 5%) between irrigations indicated that the seasonal variation in the collective network demand did not affect the hydrodynamics of the individual plot network. Thus, the regulating valves at the hydrant points worked adequately. Nevertheless, significant differences in the irrigation pressure were observed between plots, and the pressure ranged from 243 kPa to 438 kPa. The lowest irrigation pressures were at the lower limit of the suggested pressure of the current sprinkler layout (T18x18). Alternatively, the largest irrigation pressures were excessively high and self-defeating in windy areas.

On-plot supervision provided the necessary data to determine if irrigation was conducted during the day or night. The results indicated that three-quarters of the irrigations in the monitored blocks of plots 1H002 and 2H100 were applied during the day. Alternatively, in the blocks of hydrants 2H158, 2H124 and VH012, three-quarters of the irrigations were applied at night.

Preferences for daily or nightly irrigation indicated that the block irrigation sequence of the plots was not periodically modified. Irrigation schedules based on nightly irrigation may be superior in the Ebro Valley region because the night-time WDEL is one-half of daytime losses (Playán et al., 2005). In hydrants 1H014, 2H043, 1H108 and 1H092, the irrigation time was equally divided between the day and night. This type of irrigation pattern requires periodic changes in the irrigation schedule; however, according to Dechmi et al., (2004) is more efficient than fixed block sequence irrigation.

Table IV.7 presents the telecontrol data of four drip-irrigated plots. In general, the seasonal irrigation time was related to the continuous inflow rate of the hydrant, which was expressed in litres per second and hectare. The lowest seasonal irrigation time (1,026 hours) corresponded to the highest continuous inflow rate (1.9 l s^{-1} ha^{-1}), which was observed in hydrant VH100. The irrigation interval was always lower than one day; thus, the orchards were irrigated at least once per day. The irrigation time per hectare and event varied from half an hour to 4 hours per hectare and event.

Moreover, the average values presented in Table IV.7 did not show temporal variability in irrigation scheduling. Figure IV.6 presents the temporal variability of the irrigation patterns of the four selected hydrants. Hydrants 1H141 and 1H139 (Figures IV.6a and IV.6b, respectively) presented greater variability in the irrigation time throughout the entire peach cycle than hydrants VH100 and VH097 (Figures IV.6c and IV.6d, respectively). Namely, the irrigation schedule of hydrants 1H141 and 1H139 was changed almost weekly. For hydrants VH100 and VH097, the irrigation time increased more (VH097) or less (VH100) gradually with fruit development and decreased drastically at postharvest. However, the irrigation interval remained constant at less than one day and slight variations were observed throughout the crop development process.

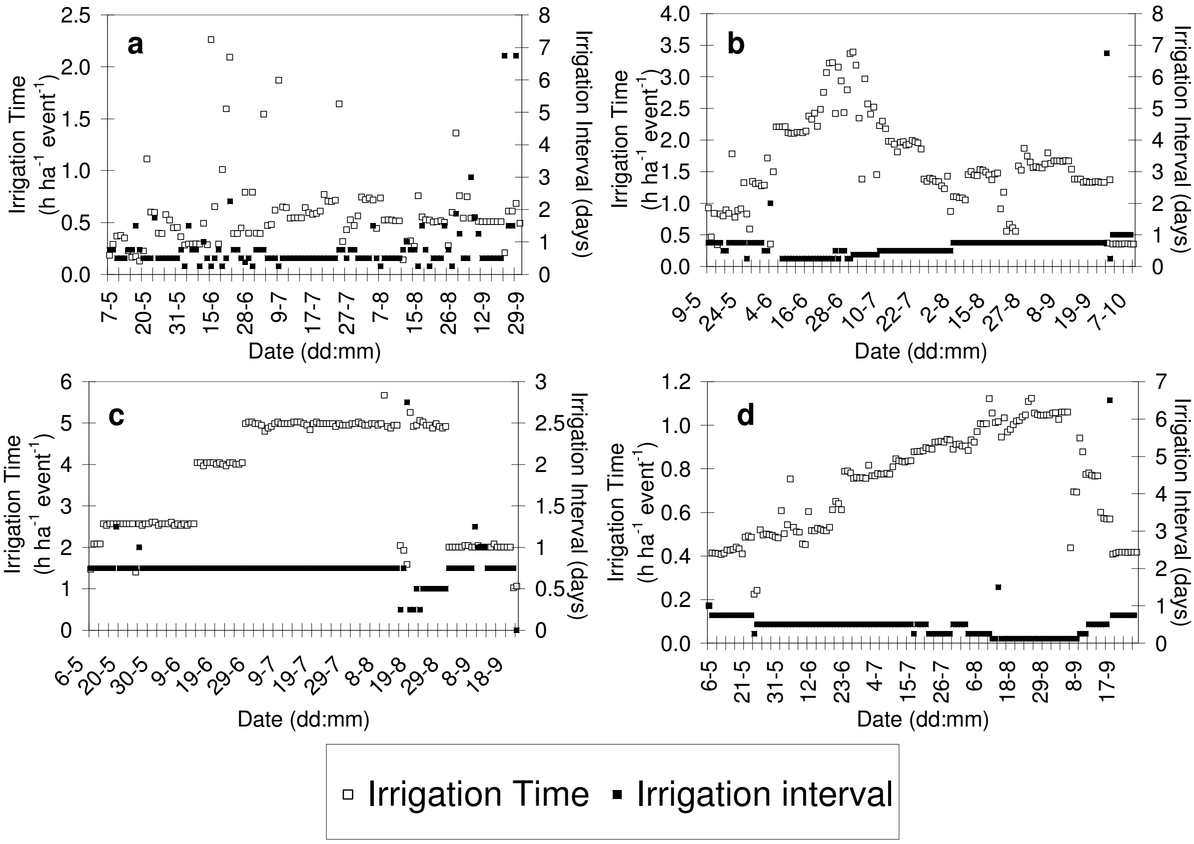


Figure IV.6. *Evolution of the irrigation time (per hectare and event in hours) and the interval between irrigation (in days) during the irrigation season, for four drip irrigated plots cropped by peaches (5a, 1H141, 5b, 1H139, 5c, VH100 and 5d corresponds to hydrant VH097).*

Table IV.7 *Telecontrol data analysis for four drip irrigated plots. Seasonal irrigation time, irrigation time per hectare and event for two representative periods of crop development (May-June and July-August) and time between irrigation in days for the same two periods. Irrigation time and time between irrigation presented in this table corresponds to the most common values for the time considered, excluding the occasional extremes.*

Hydrant	Area (ha)	Inflow rate (l s^{-1})	Seasonal Irrigation Time (h)	Irrigation Time May-June (h ha^{-1} event^{-1})	Irrigation Time July-Aug (h ha^{-1} event^{-1})	Time Between Irrigations May-June (days)	Time Between Irrigations July-Aug. (days)	Irrigation Depth (mm)
1H141	20.5	24	1314	0.50	0.60	0.70	0.90	513
1H139	5.8	6	1324	1.93	1.44	0.50	0.75	500
VH100	2.1	4	1026	3.10	4.03	0.75	0.75	629
VH097	15.1	17.5	1568	0.52	0.85	0.60	0.43	665

IV.3.4. Comparison of irrigation patterns between solid sets and pivots.

The principal difference in the irrigation scheduling patterns of solid set and center pivots was the number of opening and closing of the hydrants (irrigation events). For solid sets, the number of irrigation events during a crop season increased from 35 to 45, while the number of events for pivots was reduced to 10-20. Consequently, the irrigation time per hectare and event was larger for pivots than solid sets. The results of the on-farm irrigation analysis of the 10 solid sets revealed that the irrigation events should be obtained from the irrigation block sequence data. For pivots, telecontrol data analysis was biased because the pivot cycle times were not available and the complete irrigation sequence could not be established.

The average applied irrigation depths at the CID were 808 mm and 793 mm for pivots and solid-set systems, respectively, and significant differences between systems were not observed. In contrast, the seasonal applied irrigation depth of alfalfa was significantly different among sprinkler irrigation systems. Namely, the solid set system provided an average seasonal irrigation depth of 889 mm (with a standard deviation of 164 mm), and the pivot system provided an average irrigation depth of 793 mm (standard deviation of 120 mm). For maize, significant differences in the average irrigation depth between irrigation systems were not observed (819 mm for solid sets and 818 mm for pivots). In any case, for both systems, the variability of the applied doses was high (standard deviation of 182 mm and 225 mm for solid sets and pivots, respectively). For alfalfa, the irrigation depth of pivot plots was lower than that of solid sets due to the greater efficiency of pivot systems. Playán et al., (2005) demonstrated that water losses in sprinkler irrigation systems (pivots and lineal moves) were two-thirds lower than that of solid set systems. Dechmi et al., (2003b) studied the Loma de Quinto irrigation district of the Ebro Valley and found that the Christiansen coefficient of uniformity (CU) of center pivots (76%) was greater than that of solid-sets (68%). However, in the Loma de Quinto, solid set designs were deficient for windy areas.

IV.4. CONCLUSIONS

Variability in the irrigation depth among plots of the same crop was approximately 25%. This variability was mainly attributed to differences in the irrigation schedule. The seasonal SIPI values of the crops at the CID indicated that the farmers try to optimize irrigation water use by restricting applications on drought resistant crops (SIPI values greater than 100% were observed for sunflowers and alfalfa) and limiting water stress in drought sensitive crops (the average SIPI value of maize was 83%). Irrigation was also restricted in drip irrigated stone fruit orchards.

The monthly change in the cumulative SIPI of maize indicated that the area of maize with low SIPI values (<80%) increased from the beginning of the crop season to July and then decreased at the end of the season. Frequent and light applications are often conducted at the early stages of crop development to avoid crusting problems and to promote maize germination. In general, over-irrigated plots at the end of the season were attributed to persistent over-irrigation throughout the growing season. Thus, over-irrigated plots would benefit from an advisory service based on telecontrol data analysis.

For alfalfa, the average SIPI was 107%, which was indicative of a general deficit -irrigation pattern. Moreover, the results suggested that deficit -irrigation was repeated every cutting cycle. Namely, 82% of alfalfa plots presented SIPI values greater than 80%. As previously mentioned, SIPI values greater than the potential efficiency of the irrigation system are indicative of deficit-irrigation. Thus, the alfalfa would benefit for a telecontrol data continuous analysis following the proposed methodology. Again, the telecontrol data can be an important tool for the improvement of irrigation water management in alfalfa.

The SIPI values of stone fruits throughout the four FAO phases suggested that deficit irrigation strategies were performed on medium cycle peaches at the CID. However, the applied irrigation dose was continuously reduced throughout the crop cycle (sustained deficit), and the reductions were not applied at the recommended phases (controlled deficit); thus, the applied irrigation strategy was not based on a controlled deficit strategy.

The analysis of temporal variability of SIPI values is a valuable tool for the improvement of irrigation water management for maize, alfalfa and stone fruit at plot level. Real time SIPI analysis from telecontrol data as proposed in this research, complemented with the control of some on-farm block irrigation sequences should be implemented in the daily routines of the district office to greatly improve the irrigation management at plot level. This methodology could be easily implemented in any telecontrolled irrigation network. However, the reliability and accuracy of the methodology to determine the crop water requirements of the main crops of the CID is a key factor in the estimation of the seasonal irrigation performance indexes (SIPI) since the real values of the net irrigation requirements affect directly the SIPI values. Consideration of the NIR spatial variability along the CID also could improve the irrigation water management at plot level. This objective will require a characterization of the spatial distribution of crop water requirements.

The general irrigation patterns of solid set and center pivot systems indicated that the irrigation time per event for alfalfa was greater than that of maize. Furthermore, the short and frequent irrigation timing for maize (1-1.5 hours per block and event) could yield high evaporation losses from crop intercepted water. In general, two different patterns in the irrigation times were observed at the CID. In the first irrigation pattern, short irrigations were applied until the middle of June. Subsequently, the irrigation time was increased until the middle of August and then decreased until the end of the crop season. This irrigation pattern was employed by farmers that did not frequently alter the irrigation schedule (low intervention). Alternatively, the second pattern was characterized by continuous changes in the irrigation time throughout the crop season. This type of pattern requires significant farmer intervention because the irrigation schedule is changed almost weekly. The second irrigation pattern was observed more often with solid set systems than pivots; however, differences in the irrigation performance among the two irrigation patterns could not be established. Nevertheless, the analysis of telecontrol data is an important tool for the improvement of irrigation management in pressurized irrigation districts and can be used to promote and facilitate controlled deficit irrigation strategies on stone fruits. Telecontrol data can be a valuable tool to reduce variability of irrigation water management between plots.

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CHAPTER V: IRRIGATION AND ENERGY MANAGEMENT IN AN AUTOMATED IRRIGATION DISTRICT

IRRIGATION AND ENERGY MANAGEMENT IN AN AUTOMATED IRRIGATION DISTRICT

RESUMEN

La comunidad de regantes de Almudevar (AID), tradicionalmente regada por superficie, se transformó en riego presurizado a finales del 2010. Las parcelas se equiparon con sistemas de riego por aspersión y con un sistema muy avanzado de telemetría y control remoto que llega a controlar hasta las válvulas de sector de las parcelas. Esta particularidad le permite no sólo realizar una gestión centralizada del riego sino ejecutarla desde la oficina de la comunidad. La AID se divide en cuatro zonas independientes de riego con sus correspondientes infraestructuras. La comparación entre el antes y el después de la modernización de riego se realizó en términos de estructura parcelaria, patrones de cultivo y manejo del riego. Con los datos obtenidos del sistema de telemetría durante la campaña 2011 se analizó la evolución temporal del uso del agua y de la energía y la adecuación de la demanda energética a la potencia contratada. En el análisis del uso del agua y de la energía se realizó especial énfasis en los meses de mayor demanda (Julio y Agosto). Se determinó el índice estacional de la calidad de riego (SIPI) para una frecuencia mensual y estacional y para los cultivos principales en la comunidad de regantes. El SIPI mostró un valor medio global de 94% y una variación espacial y temporal importante. El promedio de SIPI osciló entre 85% para el doble cultivo de cebada/ maíz hasta 131% para la cebada y la desviación estándar situó entre el 18% para el maíz hasta el 69% para la cebada. La variabilidad del SIPI entre parcelas del mismo cultivo nos indica que hay posibilidades de mejora. En general, los patrones de aplicación del riego mostraron una fuerte relación y adecuación con las tarifas energéticas debido al control centralizado de la gestión del riego. Además, el análisis mostró una infra-utilización de la potencia contratada en las cuatro zonas de gestión de riego, sobre todo durante el período tarifario de alto costo (P2). Se ha identificado la posibilidad de ajustar la contratación de la potencia con el fin de disminuir el coste total. La disponibilidad de datos en tiempo real del consumo de agua de riego proporcionado por el sistema de telecontrol, y la posibilidad de analizar la demanda futura, permite la optimización de la distribución de las demandas de riego en función de las posibilidades de contratación de potencia, el período tarifario y las limitaciones de la red de riego. En futuros trabajos con más campañas de datos se analizará la potencia contratada considerando diferentes manejos del riego, alternativas de cultivo y meteorologías.

Palabras claves: telemetría, sistemas de telecontrol, eficiencia del uso del agua, eficiencia energética.

ABSTRACT

The Almudevar irrigation district (AID), a traditional surface irrigation district, was transformed into pressurized irrigation in late 2010. The plots were equipped with sprinkler irrigation systems and with a high level telemetry and remote control system which reaches the irrigated block level and permits the centralized management of the 2200 irrigation blocks from the district office. The district was divided into four independent irrigated areas with its correspondent infrastructures. Comparison between before and after the AID modernization was established in terms of land structure, crop patterns and irrigation management. The temporal evolution of irrigation water and energy demands in 2011 irrigation season and the adequacy of the energy demand with the contracted electric power were analyzed with the available telemetry data of 2011. The energy analysis was focused on the months of peak water demand (July and August). An irrigation performance index (SIPI) for a monthly and seasonal frequency was computed for main crops in the AID. The SIPI showed an overall average value of 94% but with a high spatial and temporal variation. The average SIPI ranged between 85% for barley/maize double cropping to 131% for barley and the standard deviation rises to 18 for corn and to 69 for barley. The SIPI variability showed possibilities for improvement. In general, the irrigation patterns showed a strong relationship with the energy tariff schedule due to the centralized control of the irrigation management. Also, the energy analysis showed an infra-use of the contracted power in the four irrigation zones of the AID especially during one of the high cost tariff period (P2). The possibility of adjusting the power contracting in order to decrease the total cost has been identified. The adjustment should be considered in the irrigation organization. The availability of real time irrigation consumption data provided by the telemetry and remote controls system, and the possibility of analyzing future demands, allow the optimization of the distribution of irrigation demands in accordance with the power contracting possibilities, the tariff period of the electric bill and the irrigation network limitations.

Keywords: Telemetry, Remote control systems, water use efficiency, energy efficiency.

V.1. INTRODUCTION

In the last decade, the economic growth in Spain has greatly increased water demand; however, water availability has not increased accordingly because of the lack of significant increases in water storage capacity (MARM 2006). The Spanish Government has introduced several reforms to manage water demand, such as public water rights banks, environmental taxes and subsidies for the irrigation modernization (Lecina et al., 2010a, b). In addition, new water management plans are being implemented through a participatory and integrated process following the guidelines of the European Water Framework Directive (Lecina et al., 2009 and 2010a).

One of the most important actions for water resources management is the irrigation modernization developed through the two National Irrigation Modernization Plans (*Plan Nacional de Regadíos and Plan de Choque de Modernización de Regadíos*) (MARM, 2002; MARM, 2006). The main objectives of these plans are: water conservation, technology transfer, promoting the use of alternative water resources, energy efficiency, improved farm income, creating more job opportunities and overall, promoting the Spanish irrigated lands sustainability (MARM 2010). As a result of these irrigation modernization plans, sprinkler irrigation areas have increased in Spain. According to the 2011 Areas and Crop Yields Survey (ESYRCE) (M.A.A.M.A, 2011), the total irrigated area in Spain reaches the 3,473,474 ha, of which 497,794 ha are sprinkler irrigated. The autonomous community of Aragon is the fourth community in Spain in terms of irrigated area after Andalucía, Castilla La Mancha and Castilla Leon (M.A.A.M.A, 2011).

Irrigation systems modernization involves in most of the cases the replacement of open-channel gravity-systems with pressurized irrigation pipe distribution networks with a hydrant in each farm. Also telemetry and remote systems are incorporated into the majority of modern collective pressurized irrigation networks in Spain. This type of infrastructure provides many opportunities for the improvement of irrigation system management (Damas et al., 2001; Stambouli et al., 2012). The new networks enable using water more efficiently with irrigation systems such as drip and sprinkler irrigation instead of surface irrigation (Playán and Mateos, 2006). Lecina et al. (2010a) reported that if the application efficiency of surface irrigated plots was moderate, an additional consequence of irrigation modernization could be an increase in water use and in the depleted fraction (the increase in water consumption is higher than the reduction in runoff/percolation). Also, modernization of irrigation systems often results in higher energy consumption (Abadía et al., 2008; Rodriguez-Diaz et al., 2009). For the period of 1970-2007, Corominas (2010) reported that the water used for on-farm irrigation in Spain has fallen by 21% from 8250 to 6500 m^3 ha^{-1}, since energy consumption has increased by 657%, from 206 to 1560 KWh ha^{-1} (Abadía et al., 2012).

In Spain, an important increase of energy consumption in agriculture has occurred, reaching the 3.5% of the nationwide energy consumption. The 70% of agricultural energy consumption corresponds to machinery and irrigation (IDEA, 2008). This high consumption is due in large part to the irrigation of new areas and the modernization of traditional irrigation systems. In 2001 energy consumption by agricultural machinery accounted for 47% of the total energy used by agriculture and irrigation water accounted for 22%. The forecast for 2012 is that agricultural machinery energy use will decrease to 42% whilst energy consumed by irrigation will increase to 32% (Jimenez-Bello et al., 2010).

This energy dependence of pressurized irrigation systems has been aggravated by the dramatic rise in electricity prices that have occurred in Spain since the abolition of special rates for irrigation and liberalization of the electricity market in 2008 (IDEA, 2008). The average energy costs in modernized irrigation districts increased by 82% between 2005 and 2009 (Ederra and Murugarren, 2010; Abadía et al., 2012). The energy context has led to the publication of numerous studies and methodologies to quantify and improve the energy efficiency (Abadía et al., 2010a; Carrillo-Cobo et al., 2010; Moreno et al., 2010a; Moreno et al., 2010b; Moreno et al., 2010c; Carrillo-Cobo et al., 2011; Lamaddalena and Khila, 2011).

Energy efficiency of a new and well-designed pressurized irrigation network relies principally on water efficiency and on management efficiency. It is not enough to apply the irrigation according to crop water requirements but it is necessary to arrange the water application at the low cost energy periods maintaining a high efficiency of the pumping stations.

Irrigation performance analysis are profusely found in the literature to characterize water use efficiency in pressurized irrigation districts (Faci et al., 2000; Dechmi et al., 2003; Lorite et al., 2004a, b; Stambouli et al., 2011; Salvador et al., 2011). All these works found high spatial variability on irrigation performance indicators and concluded that the variability between farms indicates potential for improvement. This type analysis is also needed to control energy use efficiency and fortunately, the telemetry and remote control systems provide the necessary data (Stambouli et al., 2011) to perform them.

The sharp rise in electricity prices and agricultural inputs (fertilizers, seeds, pesticides ...) jointly with the fluctuating crop prices can shake the profitability of irrigated farms over all in recently modernized districts. Lecina et al. (20010) stated that the results obtained in the post-modernization scenarios will also depend on factors other than irrigation, like the evolution of agricultural and energy prices. In order to optimize the multiple factors affecting the profitability of farming, analytical tools should be used to make appropriate decisions under different situations. On the other hand, increased environmental awareness about the scarcity of water resources makes research in this field of great importance.

This research analyze the water and energy management of a recently modernized district located in north-eastern Spain that has installed a highly automated telemetry and remote control systems and evolves from a surface irrigation system. The modernized district requires a high standard of water and energy management to control the water use and its application cost, especially the electricity cost, to be competitive. The water and high cost energy-limited future are the catalyst that force many of the existing automatic agricultural technologies to work together for the irrigated agriculture.This work proposes a methodology to incorporate the telemetry and remote control data and its analysis in the modern telecontrol irrigation networks routines to i) improve the irrigation performance at the plot level and ii) to control the electricity cost of the district.

The objectives of this research were to: (1) analyze the seasonal and monthly on-farm irrigation performance at the plot level by assessing the continuous irrigation performance index (SIPI) and to compare them with the pre-modernization situation; (2) characterize the irrigation scheduling patterns at the plot level; and (3) identify the adequacy of the irrigation patterns with the energy demand criteria and to investigate the district's water management plan to minimize electricity costs considering energy demand costs and power contract adjustment.

V.2. MATERIAL AND METHODS

V.2.1. The Almudevar Irrigation District evolution

The study area is the Almudevar Irrigation District (AID) located in La Violada Gully watershed located in the middle part of the Ebro River Basin in north-eastern of Spain (Figure V.1). The watershed has an area of 19,637 ha but the district occupies only 3,744 ha of irrigated land. The AID is integrated in the Monegros I irrigation scheme and is surrounded by three canals: the *Monegros Canal* at the northeast, the *Violada Canal* at the west and the *Santa Quiteria Canal* at the south. Until 2008, the 94% of AID area was surface irrigated with blocked-end plots, 5% was sprinkler irrigated and 1% was drip irrigated. The irrigation district was transformed entirely in pressurized irrigation systems and finished the modernization process in late 2010 (94%of the area with solid-set, 5% with center pivots and lateral move systems and 1% with drip irrigation systems). In the modernization process the AID was equipped with a telemetry and remote control irrigation system allowing the remote management of all the hydraulic valves (290 hydrants and 2200 irrigation blocks) of the irrigation networks (general and on farm) from the district office. The collective irrigation system operates in an organized on-demand scheme. Although irrigation execution can be controlled and centralized from the district office by the remote control system, the irrigation schedule should be performed by grower demands and district manager intervention. The farmers communicate their irrigation requirements (irrigation hours and days) to the manager with a daily or weekly frequency. The manager manually performs the daily irrigation schedule of the entire district organizing the farmers' irrigation demands taking into account its preferences, the energy cost and the available power at each energy tariff period.

Before the modernization process, the AID irrigation system was originally designed to irrigate winter cereal and the capacity of the irrigation ditches was very limited (Faci et al., 2000; Playán et al., 2000), as a consequence the irrigation intervals were very long. Another important problem in the AID was the high seepage losses of the Violada Canal due to the high gypsum content of the layout of the canal. The maintenance and reparation work of the Violada Canal was so important that the construction of a new Canal was initiated in year 2000. During the 2004 irrigation season, the new Violada Canal was finished and started to deliver water to the AID, reducing in a great amount the seepage losses from the canal. This reduction of canal seepage affected the flow regime of La Violada Gully and allowed a better supply of irrigation water to higher water demand crops such as maize and alfalfa (Barros et al., 2011a, b).

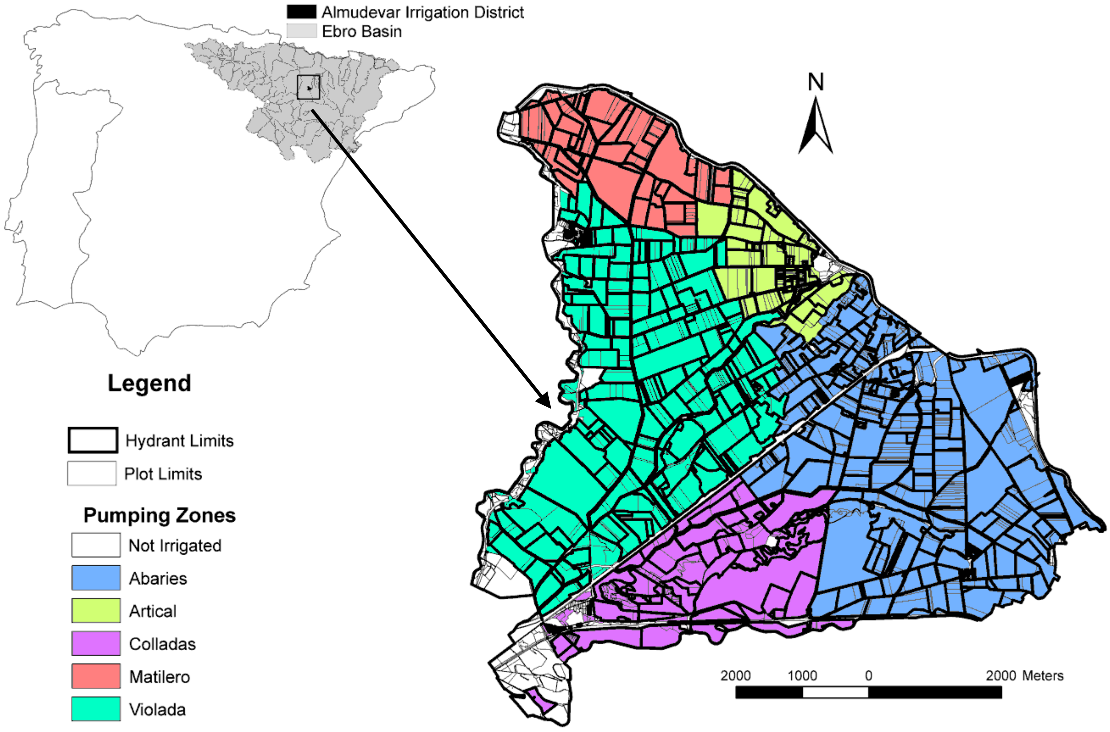


Figure V.1. *Location of the AID in the Ebro Basin in north-east Spain. Plots, hydrants limits and the independent irrigation zones were presented.*

The first phase to modernize the AID was the land consolidation. As a result of this process, a farmer would get a single plot in the district with an area similar to the amount of plots he owned before the consolidation. The former district was characterized by a high number of partial time farmers, with only 20% of them fully dedicated to agriculture. Even after the modernization process many farmers lease plots and manage irrigation in plots other than their own. The irrigation management units are composed of the plots belonging to the own farm plus the leased plots. Therefore, the irrigation management unit does not necessarily match farm or plot sizes. Changes in land ownership and tenure structure will be analyzed.

The modernized AID is divided into five irrigation zones (Figure V.1), including three independent irrigation systems (Abariés, Colladas and Matilero) and two interconnected zones (Violada and Artical). Each zone has one reservoir (except Matilero that contains 2 reservoirs called Matilero I and II), a pumping station and an independent distribution pipe network. The Violada and Artical zones have two reservoirs, two pumping stations and two general pipe networks interconnected and in the present work will be considered as a single irrigation area. Therefore the data analysis of the 3,744 ha of irrigated land of the AID was performed for each of these four irrigation areas individually. The total storage capacity of the reservoirs of the AID is 635,160 m3.

The total installed pumping power capacity in the four management irrigation zones is 6,361 kW allowing the irrigation of the AID with a maximum flow rate of 6,000 L s^{-1}, this flow is sufficient to supply water to the 60% of the AID area, simultaneously. The justification for the execution of 4 zones of irrigation management is to obtain greater independence of each of these areas. A programmable robot manages remotely the pumping equipment operation and the associated electromechanical operations at the district control center.

V.2.2. The telecontrol irrigation system

The telemetry and remote control system consists of a control center unit (PC unit) that communicates by radio wireless with the communications center located in the highest point of the AID (Almudévar Castle Tower). From this point, the irrigation schedules programmed in the control center unit were sent to seven control units, which are responsible to distribute remotely the correspondent commands to the hydrants and irrigation block valves. Each control unit was provided with a memory card allowing the accumulation of over 200 schedules. The system produce continuously, every 10 minutes, a "refreshment" of information (update), a radio communication ordering the hydrant situation (open, closed, open a determined irrigation block hydraulic valve, open the general hydrant hydraulic valve, etc)

The telemetry and remote control system was set to operate at three levels: hydrant, plot and irrigation block (IB, area that irrigates simultaneously from a hydrant). The telecontrol system of the AID differs from other Water User Associations (WUA) systems in the level of remote control. Since in others WUA the telecontrol only reaches the hydrant hydraulic valves, the telecontrol of the AID reaches the irrigated block valves and the AID telemetry system provides data at the level of the irrigated blocks valves. The difference allows the remote schedule and irrigation execution of all the hydraulic valves from the AID office. The system records variables such as the irrigation volumes and times, the irrigation sequences of the IB and the pressure of the control points. Hydraulic data as pressure or discharge in selected points were used to supervise the irrigation network status (breakdowns, opening and closing of the hydraulic valves) and to control incidences.

V.2.3. Meteorological characteristics and net irrigation requirements

The nearest automatic agro-meteorological station from the SIAR network (www.magrama.gob.es/siar/informacion.asp), Tardienta station (41º 58´ 14´´N; 0º 30´ 24´´W), provided daily data from January 2006 to December 2011.

Crop evapotranspiration (ET_c, Equation V.1) was estimated from reference evapotranspiration (ET0) and the appropriate crop coefficients.

$$ET_c = K_c ET_0 \tag{V.1}$$

Reference evapotranspiration (ET0) was computed on a daily basis by applying the Penman-Monteith (Smith 1993) method to the 2010-2011 meteorological data. The crop coefficients values at the initial, medium and end of the crop stages ($K_{c\ ini}$, $K_{c\ med}$ and $K_{c\ end}$) and the general lengths (L) for the different growth stages (L_{ini}, L_{dev}, L_{mid} and L_{late}) and the total growing period were taken from Allen et al., (1998) and complemented with local information (Martinez-Cob et al., 1998). Values of K_c for maize were estimated using the thermal units methodology proposed by Martínez-Cob (2008). This methodology shows very good agreement with weighting lysimeters data in the Ebro Valley region. Net Irrigation requirements (NIR, equation V.2) were calculated using the standard FAO procedures, as described by Allen et al. (1998). Following these procedures, Penman–Monteith reference evapotranspiration (ET_0), crop coefficients (K_c), crop evapotranspiration (ET_c) and effective precipitation (EP) were estimated for all crops and study years. EP was calculated using the empirical method using the USDA method (Cuenca, 1989). Net irrigation requirements (NIR) were determined for the irrigated crops in the AID during 2010 and 2011 irrigation seasons.

$$NIR = (K_c\ ET_0) - EP \tag{V.2}$$

V.2.4. The seasonal irrigation performance index in the AID

The performance parameter used to characterise the water use in the AID was the Seasonal Irrigation Performance Index (SIPI) (Faci et al., 2000). The SIPI was defined (equation V.3) as the seasonal percentage of the Net Irrigation Requirements (NIR, mm) to the seasonal irrigation depth delivered to the crops (ID, mm). The irrigation delivery depths were obtained from telecontrol records. The SIPI values represent a simplification of the irrigation efficiency standard concept defined by Burt et al. (1997) and Clemmens and Burt (1997).

$$\text{SIPI} = \frac{\text{Net Irrigation Requirements (NIR)}}{\text{Irrigation Depth (ID)}} * 100 \qquad \text{(V.3)}$$

Some authors (Molden and Gates, 1990; Kalu et al., 1995; Faci et al., 2000, Malano and Burton, 2001; Lorite et al., 2004) have defined several indicators characterizing irrigation system performance in order to evaluate current practices and recommend improvements in irrigation efficiency and water productivity. These performance indicators are also used to quantify the system ability to achieve the objectives established for an irrigation area or to assess the current performance of the system relative to its potential.

A SIPI value of 100% implies that irrigation water application is equal to the net crop water requirements. This situation can not lead to a fulfilment of water requirements since 100% irrigation efficiency cannot be attained under commercial field conditions. Clemmens and Dedrick (1994) classified irrigation systems according to their potential application efficiency. In an optimistic scenario, the best systems attained 90% efficiency. If water application is made equal to the net irrigation requirements with an efficiency of 90%, the resulting SIPI value is equal to the irrigation efficiency (90%). Under this efficiency hypothesis, any SIPI value above 90% implies seasonal under-irrigation. Accordingly, SIPI values under 90% imply seasonal over-irrigation. Since SIPI is a seasonal index, during short period's percolation may happen even with SIPI ≥ 90%, and deficit may happen even with SIPI≥ 90%. A detailed analysis of a particular irrigation system would be required to assess its efficiency, and therefore to establish the specific SIPI value separating seasonal deficit from seasonal excess irrigation. A short period analysis for the SIPI index will provide a better approach for water use analysis. Monthly SIPI values were characterized for each crop and the spatial and temporal variability of the index was analysed.

V.2.5. Analysis of solid-set irrigation patterns in the AID

For each hydrant of the AID system, the seasonal number of irrigation events, the seasonal irrigation time, the seasonal irrigation depth, the time interval between irrigation events, the irrigation sequence of its irrigated blocks, the time and depth of each irrigation event, and the changes in irrigation schedules throughout the crop season were determined. Changes in hydrant irrigation schedules were analyzed dividing the crop season in two periods with high differences in irrigation requirements, first period from April to June and second period from July to August. Irrigation schedules were also analyzed considering the number of irrigation blocks per hydrant.

During the first irrigation season after the modernization (year 2010), due to preliminary running problems, the telecontrol system recorded irrigation data only at the hydrant level. For this reason, ten solid set plots (5 maize plots, 2 alfalfa plots, 1 rice plot and 2 sunflower plots) were supervised to determine the block irrigation sequence and the pressure at the sprinkler level. A pressure transducer with an incorporated Datalogger (Dixon PR300) was installed in the middle of the sprinkler riser in a representative block of each monitored plot. Work pressure data were recorded every 15 min. The monitored irrigation block was similar in size and layout to the other IB within the same plot. Data collected from the pressure logger were used to analyze the irrigation time, the number of irrigation events, the daytime and nighttime irrigation and to determine the irrigation pressure and its variability throughout the irrigation season. During irrigation season 2011, telemetry and remote control system operated at the irrigation block levels and data for irrigation time, depth and schedule were available and pressure transducers were not used.

V.2.6. Analysis of adequacy of the power contracted at each energy tariff period

The pumping stations at the AID use electric pumps with frequency regulators in order to optimize the pumps performance according to the variation of water demand along the irrigation season. The AID has an electricity supply contract with hour discrimination (six energy periods with different cost) imposed by the electric power companies. The manager of the irrigation district must decide each year how much power to contract. The first 2 years of operation with the pressurized network are serving the AID to adjust the contracted electric power to the power demands. To contract the adequate power at any energy period prevent the payment of non-used power (over contracting) and avoid the penalization cost due to excessive power demand (under contracting).

To control the electric bill of a well-designed irrigation district it is important: to maintain high efficiency of water use, and of the pumping operation, to arrange the water application to the periods of low cost energy and to contract the strict necessary power at each tariff period.

The energy management analysis was performed with the telecontrol records during the 2011 irrigation season. This year the AID was fully irrigated with the new system and hourly records of irrigation times and irrigation volumes were available. The 2011 irrigation season can be considered as a normal average season, different from the 2010 characterized by a low water demand crop pattern (the on farm irrigation networks were not fully equipped) and also different from the 2012 because of important water constraints.

Demand curves versus time were established for each irrigation management zone and tariff period, both in terms of water volume (m^3) and energy demand (KWh). Energy demand curves were estimated assuming a homogeneous Energy-Volume ratio (KWh m^{-3}) for each irrigated zone. The ratio was estimated for each irrigated zone from the total energy consumption reported in the electricity bills and the total volumes of irrigation water pumped obtained from the telecontrol system. Farmer's Irrigation patterns were analyzed in terms of energy consumption and adequacy to the contracted power. Other power contracted scenarios were analyzed and compared with the current one. Also, changes in irrigation management were proposed.

Several indicators [Energy consumption (KWh); Energy cost (€); Energy consumption per irrigated area (KWh ha-1); Energy cost per irrigated area (€ ha-1); Energy cost per 1000 m^3 (€ m-3)] were used to characterize the AID energy performance along the 2011 season. These indicators are commonly used in the related literature (Malano and Burton, 2001; Rodriguez et al., 2005; Ruiz et al., 2007; Abadía et al., 2008; idea, 2008; Moreno et al., 2007; Moreno et al., 2010c; Carrillo Cobo et al., 2010; Jimenez-Bello et al., 2010). The indicators were used to analyze the power contracted scenarios.

V.2.7. Further statistical analyses

The statistical analysis of the dataset was performed using the Statgraphics Plus software (version 5.0, Statistical Graphic Corp. 1994-2000). The analytical procedures involved principal components analysis, ANOVA, Duncan's multiple means comparison and cluster analyses. First, a hierarchical cluster analysis was used on four variables: quantitative (NIR, irrigation depth) and categorical (crops, irrigation block per hydrant). This classification was performed to identify homogeneous groups of irrigation performance in the AID. To better understand factors affecting water use and the SIPI, Duncan's multiple means comparison was applied to study the interaction between the homogeneous groups as the result of the cluster analysis.

The telecontrol data were used to elaborate statistics about frequencies and general patterns of the farmers´ behavior.

To analyze the influence of meteorology on solid-set sprinkler irrigation decision making, non-parametric correlations were used, determining Spearman's Rho (rs). The meteorological factors used for this study included semi-hourly wind speed (U), air temperature (T), relative humidity (RH) and daily precipitation (P).

V.3. RESULTS AND DISCUSSION

V.3.1. Meteorological characterization

The mean annual temperature in the AID was 12.7ºC in 2010 and 14.2ºC in 2011. These values were slightly similar to the 6-year (2006-2011) average temperature (13.6ºC). The total annual precipitation was 379 mm in 2010 and 278 mm in 2011. The first was quite similar and the second significantly lower to the average of the 6-year data register (348 mm). The precipitation distribution along 2011 was quite irregular. Only 11.3 mm of effective precipitation occurred during the months of June, July and August, while the average precipitation for these months was 55 mm. Annual reference evapotranspiration (ET_0) calculated by the Penman-Monteith method was 1271 mm (2010) and 1303 mm (2011), these values were similar to the averaged 6-year database (1284 mm). The most frequent wind directions are northwest (locally denominated Cierzo, dry and cold) and southeast (locally denominated Bochorno, dry and hot) with an annual average speed (2-m above ground level) of 2.7 m s^{-1} (2011) and 2.4 m s^{-1} (2010), classified as moderate wind (Martínez-Cob et al., 2010). In general, only the total precipitation was significantly different in the two studied years resulting in different net irrigation requirements of the main crops (NIR).

V.3.2. The changes in AID with the modernization

Table V.1 presented the general characteristics of the AID before and after the modernization process. Before the modernization, a total of 610 land owners (Table V.1) composed the AID, owning a total of 2339 plots, according to the 2005-2008 management database of the AID. The average area of the plots before the consolidation process was 1.7 ha, and only the 28% of all the plots had an area larger than this average value. About 60% of the farms in the district included two or more separate plots. After the consolidation and modernization processes, the final number of plots in the AID was reduced to 905 with 502 land owners and its average area was increased to 4.1 ha. Also the farm size (total area owned by a farmer) increased considerably (from 6.7 ha to 7.4 ha, on average) and 71% of the farmers own plots larger than 5 ha. This new land ownership structure was necessary to afford the modernization cost of the irrigation system infrastructures. Esquiroz and Puig (2001) established a minimum plot size of 5 ha to install a hydrant, and the average hydrant size of the AID after the modernization was 12.5 ha. The average number of separate plots by farmer was reduced from 3.8 to 1.8 (Table V. 1). Major crops before modernization (2005-2008) were alfalfa, winter cereal and maize with the 45%, 28% and 11% of the total irrigated area, respectively (Table V.1). The irrigation management units are composed of the plots belonging to the own farm plus the leased plots. Therefore, the irrigation management unit does not necessarily match farm or plot sizes. Also the irrigation management unit has increased from 25 ha to 35-40 ha. Irrigation practices in the pre-modernized AID were the most labor and time consuming activities of the agricultural production of field crops. The time and labor cost of irrigation activity has been drastically reduced with the modernized sprinkler irrigation system and the farmers can afford manage more land. Although crop distribution has changed with the modernization process (Table V. 1), the AID is still characterized by field crops.

Table V.1. *General characteristics of the Almudevar irrigation district before and after irrigation modernization.*

	Before Modernization (2006 to 2008)	After Modernization 2011
Total area (ha)	4087	3744
Number of farmers	610	506
Number of plots	2339	905
Average plot size(ha)	1.7	4.1
Average farm size (ha)	6.7	7.4
Number of plots by farm	3.8	1.8
Average management unit size (ha)	25	35-40
Major Crops	Alfalfa (45%); Winter Cereal (28%); Maize (11%)	Double Cropping (52%); Maize* (18%); Alfalfa (14%); Winter cereal (10%)

** This area did not account for the maize as a double cropping*

Table V. 2, presents for each irrigated zone of the AID, the irrigated area, the number of hydrants, the number of plots, the average area of a plot, the number of plots per hydrant, the number of irrigated blocks per hydrant and the pumping established head. The largest zone was Artical-Violada (1628 ha) followed by Abariés (1320 ha), Colladas and Matilero were the smallest and similar in size (around 400 ha). The average number of plots by hydrant is higher in the biggest zones (Artical-Violada and Abariés) than in the smallest ones (Matilero y Colladas). Irrigated areas with small plots resulted in a large percentage of shared hydrants that impose irrigation management constrains (Zapata et al., 2007). Farmers sharing the hydrant should arrange their plots irrigation schedules to avoid overlapping. On the other hand, the large percentage of shared hydrants is compensated with a lower number of irrigated blocks per hydrant in these zones (Table V. 2), reducing the required irrigation time of the hydrant.

Table V.2. *General characteristics of the four irrigated zones in the Almudevar Irrigation District (AID).*

Irrigated zone	Total area (ha)	Number of hydrants	Number of plots	Average plot size (ha)	Number of plots per hydrant	Number of blocks per hydrant	Pumping pressure head (m)
Abariés	1320	109	363	3.6	3.3	4.9	79
Artical-Violada	1628	122	391	4.2	3.2	6.2	68-72
Colladas	405	28	67	6	2.4	7.2	72
Matilero	391	31	84	4.7	2.7	6.4	72

During the 2010 irrigation season, only the 80 % of the cultivated area was irrigated, the remainder 20% was rainfed area (generally cropped by barley) while in 2011 all cultivated area was irrigated with the new system (sprinkler and drip irrigation). The on farm irrigation systems installation was complete at the end of 2010 and the farmers did not risk to crop high investment crops as corn or alfalfa in this season. In 2011 all sprinkler irrigation systems were already installed and in operation. For this reason, the 2010 irrigation season is not very representative in terms of cropping patterns and irrigation performance analysis.

Figure V.2, shows the crop distribution in the AID during 2011 irrigation season. The major crops during 2011 were double cropping, maize and alfalfa representing the 52%, 18% and 14% of the total area, respectively. The modernization process has fostered a very important area under double cropping, generally winter cereals followed by a short-cycle maize. For the four irrigation zones in 2011, double cropping occupied the largest area (61% of Artical-Violada, 48% of Abariés, 38% of Colladas and 64% of Matilero), followed by maize, except in Matilero where alfalfa was the second most important crop. The area occupied by maize (as a single crop and considered long-cycle maize) has increased when considered the pre-modernization years of 2005 to 2008 (5%, Barros et al. 2011) and decreased when considered the pre- modernization years of 94-98 (around 50%) of the area. The pre-modernized crop distribution in the AID area can be characterized as 25% of winter cereal and around 70% distributed between the two major summer field crops, maize and alfalfa (depending on crop prices). The post-modernized crop patter in the AID was principally characterized by the high area devoted to double cropping (52%).

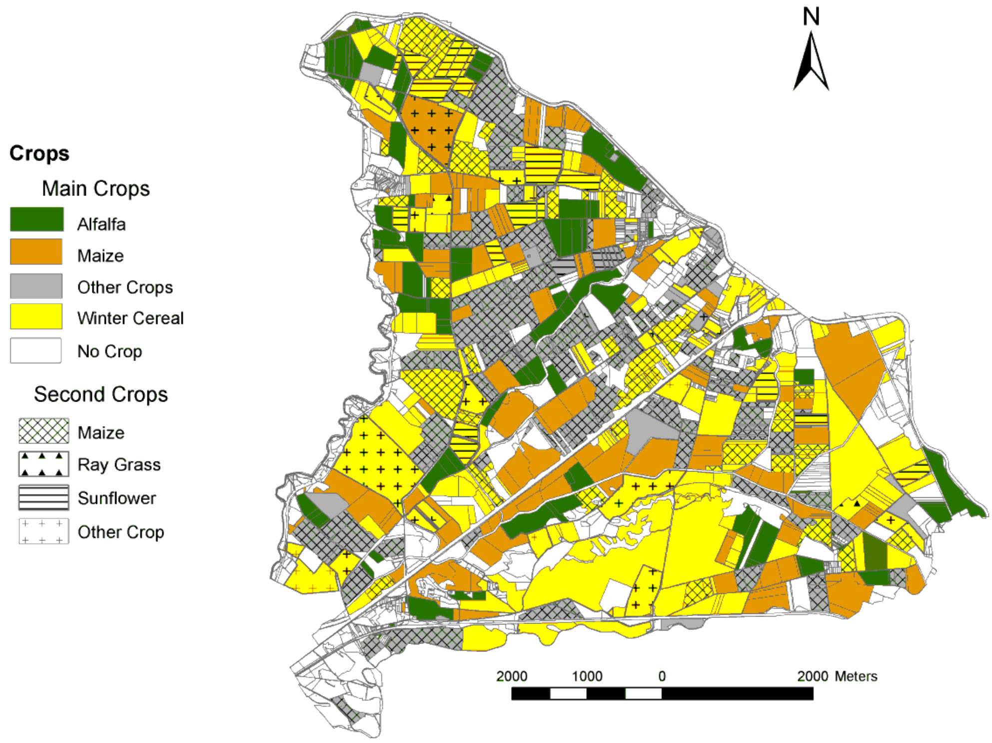


Figure V.2. *Crop distribution in Almudevar Irrigation District (AID) during 2011 irrigation season*

V.3.3. Irrigation performance at the AID

Table V.3 presents for the principal crops in the AID, its area, estimated net irrigation requirements and applied irrigation dose in 2011 season. The average seasonal irrigation requirements were 6422 m^3ha^{-1} and the average application doses were 6610 m^3ha^{-1}. For the pre modernized situation, years 2006-2008, Barrios et al., 2012 reported an average NIR of 5438 m^3ha^{-1} and an average application dose of 7362 m^3ha^{-1}. The change in crop patters after the modernization process has increased the water consumptive use in the AID (18%). On the other hand, the change of the irrigation systems has decreased the average irrigation depth (10%). Comparing the average irrigation applied dose before and after the modernization for the different crops a general decrease was observed in all crops after the modernization. Summarizing, the modernization process in the AID increased the water consumptive use because of a more intensive cropping pattern and improved irrigation efficiency reducing runoff and percolation losses.

The SIPI ± SD district-wide mean value for major crops was 94% ± 45 (obtained as the average of all the plots) that was higher than the 70% SIPI value reporter by Faci et al. (2000) for the AID before the modernization process. The 94% SIPI value indicates that on the average, the AID crops were slightly under-irrigated in 2011 irrigation season, considering a high irrigation efficiency of 90%. In general, the highest variability of the SIPI corresponds to the winter crops (barley and wheat, error bars on Figure V. 3.e) and could be primarily attributed to variability in irrigation management (Salvador et al., 2011). However, these global SIPI values should be handled with great caution due to the large differences between crops and farmers.

Table V.3. *Area (ha) of the major crops, seasonal net irrigation requirements (NIR, m^3 ha^{-1}) and seasonal irrigation (m^3 ha^{-1}) in the Almudevar Irrigation District .during the 2011 irrigation season. Values in parentheses indicate de coefficient of variation (%).*

Crop Season	Crop	Area (ha)	Net Irrigation Requirements (m^3 ha^{-1})	Irrigation doses (m^3 ha^{-1})
2011	Alfalfa	419.1	9380	8796 (20)
	Barley	295.0	1419	1085 (89)
	Maize	563.0	7295	8253 (20)
	Barley/Maize	302.3	6696	7818 (48)
	Ray Grass/Maize	201.5	8162	8863 (26)
	Peas/Maize	36.9	8876	10298 (18)
	Vetch/Maize	420.1	8260	8371 (30)
	Sunflower	26.9	6524	6558 (03)
	Wheat	171.2	2173	2196 (76)
	Other Double Cropping	318.3	6624	6175 (48)
	Barley/Alfalfa	172.1	2572	2450(65)
	Barley/Sunflower	89.6	3880	3342 (86)

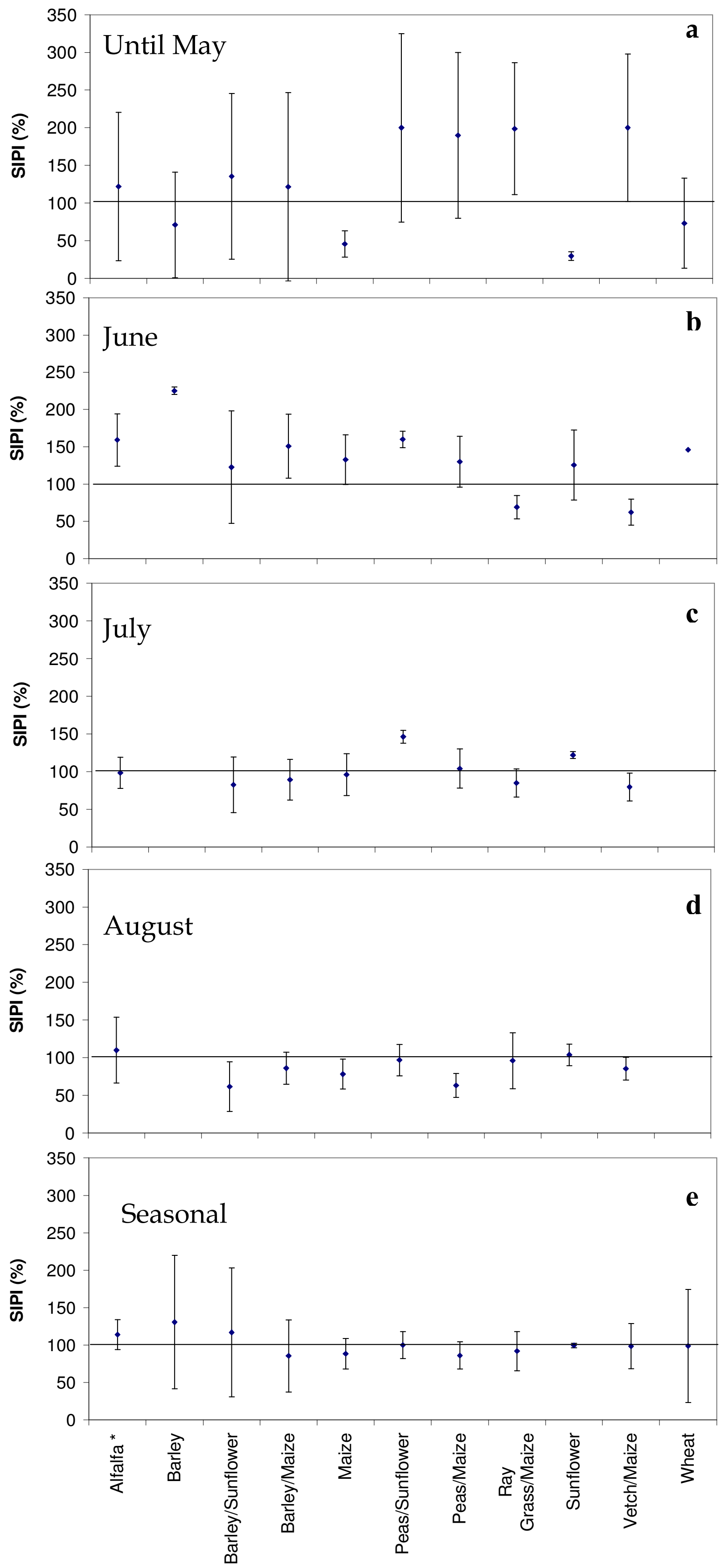
Monthly evolution of SIPI for major crops during 2011 irrigation season is presented in Figure V.3; until the end of May (Figure V. 3.a), June (Figure V.3.b), July (Figure V.3.c), August (Figure V.3.d) and seasonal (Figure V.3.e). The SIPI variability within plots of the same crop was evaluated by the standard deviation (error bars in Figure V.3) and the coefficient of variation (CV). A large variability in the SIPI values indicates a substantial potential for irrigation improvement. Monthly SIPI analysis allows a more detailed analysis between irrigation applied and crop irrigation requirements.

Seasonal SIPI values for major crops varied from 85% (barley-maize double cropping) to 131% (barley). On seasonal basis only alfalfa, barley and the double cropping barley-sunflower were slightly under irrigated, the other crops with a seasonal SIPI values lower than 100% resulted over-irrigated. For the sunflower the CV is low (3%) and for the maize, peas-maize and peas-sunflower double cropping the CV is moderate (20%, 18% and 18%, respectively) indicating that for these crops the irrigation depth applied is quite similar between farmers. SIPI values for barley, wheat and barley-sunflower double cropping showed the largest variability when compared to the other crops; these crops had the lowest number of irrigation events. In general SIPI average values of double cropping were adequate, except for the barley-sunflower double cropping (117% ± 86%) that presented also a large variability. The SIPI variation for major crops in 2011 was lower than in 2010 irrigation season (data not presented).

From the beginning of the irrigation season until end of May, the SIPI values for all studied crops except barley, maize, wheat and sunflower, were larger than 100% indicating under irrigation practices (Figure V.3.a). SIPI variability within each crop was generally high (except for maize and sunflower), and could be primarily attributed to variability in farmer's irrigation management during this period of low NIRs. This variability was decreasing in the following months. During July and August (Figure V.3.c and V.3.d, respectively), the months with highest crop water requirements, the SIPI values were close to 100% and the variability between plots decrease significantly for most of the crops. This trend but with a low intensity was also observed in other studies of sprinkler irrigated areas (Stambouli et al., 2011). Probably the central and remote management of the irrigation demands homogenizes farmer irrigation patterns along the season.

Average SIPI for maize was 88% ± 20% in 2011, this value resulted much higher that the value of 50% reported by Faci et al. (2000) for the AID before the modernization process. The value of 88% resembles a value of irrigation efficiency for sprinkler systems since the value of 50% was an average value of the irrigation efficiency of surface irrigation systems (Playán et al., 2000). Monthly SIPI for maize indicates that until the end of May maize crop was over irrigated (Figure V.3a) due to the application of slight and frequent irrigations to promote germination and to avoid the formation of a crust on the soil surface (common practice in the study area). The excess of water applied at the beginning of the crop development stages is compensated with a slight infra irrigation in the following moths.

The seasonal SIPI average value and CV of sunflower, 99% ± 3%, indicate that the crop was slightly stressed. Faci et al. (2000) reported SIPI values of 116% for sunflower for the pre-modernized AID. Other studies in sprinkler irrigated sunflower in the middle Ebro (Dechmi et al., 2003; and Skhiri and Dechmi, 2012b) reported largest level of stress with SIPI of 142% and 117%, respectively. As reported by the authors, the farmers did not consider yield as the main source of income because the sunflower subsidies were comparatively high in the years of study.



** **Corresponding to four cutting periods***

Figure V.3. *Average values of monthly (a, b, c and d) and seasonal (e) irrigation performance index (SIPI) for major crops in 2011 irrigation season. Error bars indicate ± standard deviation.*

Average SIPI for alfalfa for the whole season was 114% ± 20% which is indicative of under irrigation. In general, the seasonal SIPI analysis revealed that the dose of applied irrigation was slightly lower than the seasonal net irrigation requirements. Moreover, the SIPI values of individual cuts (identified by the different moths in Figure V.3) resulted larger than 100% except for the July cut (94%) indicating deficit irrigation and suggesting that a revision of the crop water requirements estimates is needed.

Table V.4 illustrates general trends and SIPI values for the four groups resulted from the cluster analysis. The Duncan's multiple means comparison analysis indicates that the crop (NIR) was the only significant variables that explained the water use and the SIPI for the 2011 irrigation season (Table V.4). The SIPI of high NIR crops (Alfalfa, Maize and double cropping with maize as second crop) were significantly ($P < 0.01$) different from that of low-medium crops (wheat, barley and double cropping with sunflower as second crop) in the 2011 irrigation season.

The corn SIPI values were 6% smaller than the alfalfa SIPI values. The relationship found between classes of irrigated blocks per farm, plot area and SIPI values indicated no significant differences. There is no relationship between plot area and SIPI values for the studied years.

A more detailed analysis to found combined factors affecting the irrigation performance was established using the principal component analysis and the cluster classification. As a result, four combined groups (High and Low-Medium NIR) and block irrigation number groups (<8 and ≥ 8) were found.

Table V.4. *Results of the principle factor analysis; cluster analysis and the Duncan's multiple range tests procedure used to characterize the factors affecting the seasonal irrigation performance index (SIPI). N presents the number of plots*

Cluster classification	Crop NIR	Block number	Area (%)	N	SIPI (%)	Average farm area (ha)
A	High	< 8	19	103	92^{a}	4.7
B	High	≥ 8	57	102	100^{a}	14.3
C	Low-medium	< 8	5	32	209^{b}	4.1
D	Low-medium	≥ 8	19	30	159^{c}	16.4

a, b and c: $P< 0.01$

Crop NIR

High	***Alfalfa, Maize, Double cropping (maize 2nd crop)***
Low-medium	***Wheat, Barley, Double cropping (Sunflower 2nd crop)***

Significant differences on SIPI values were obtained between plots of high NIR and low-medium NIR, being the high NIR crops more adequately irrigated than the low-medium ones (more stressed). A slight and non-significant increase of SIPI was detected when increasing the number of irrigated blocks per plot, for the plots cropped with high NIR (between groups A and B). The same analysis was conducted only for the month with highest irrigation requirements (July), for the high NIR crops (Table V.5).

Results presented for each crop showed the SIPI comparison between plots of less than 8 irrigated blocks and plots with equal or more than 8 irrigated block. Not significant differences on $SIPI_{July}$ were found for the high NIR crops except for the barley-maize double cropping, where $SIPI_{July}$ decreased significantly with the number of irrigated blocks (from 95% to 111%). For double cropping, barley-maize and ray grass-maize the applied irrigation dose was significantly reduced for large plots probably due to the high crop water requirements and the hydrant irrigation time limitation. Average $SIPI_{July}$ for alfalfa, was 127%, higher but not significant than the average SIPI (108%); indicating that deficit irrigation was systematically applied to this crop.

Table V.5. *Water use (ID, $m^3\ ha^{-1}$) and irrigation performance index (SIPI, %) for alfalfa, maize and double cropping in the month of July. Duncan's multiple comparison procedure (between groups with less of 8 IB per hydrant and more than (<8) and more than 8 IB per hydrant (≥ 8)) was used to characterize the irrigation depth and the seasonal irrigation performance index (SIPI, %). Values in parentheses represent the coefficient of variation.*

Crop	**Number of IB per hydrant**					
	< 8			**≥ 8**		
	N	**ID ($m^3\ ha^{-1}$)**	**$SIPI_{July}$ (%)**	**N**	**ID ($m^3\ ha^{-1}$)**	**$SIPI_{July}$ (%)**
Alfalfa	12	1963 (27)^a	126 (25)^a	25	1898 (21)^a	128 (26)^a
Maize	38	2629 (52)^a	95 (24)^a	26	2433 (19)^a	105 (20)^a
Barley-maize	21	2342 (39)^a	95 (30)^a	15	1825 (38)^b	111 (31)^b
Vetch-maize	20	2304 (22)^a	93 (23)^a	20	2401 (17)^a	88 (24)^a
Ray Grass-maize	16	2704 (38)^b	85 (39)^a	9	2313 (21)^b	91 (19)^a

a and b: (P< 0.01)

V.3.4. Solid-set irrigation management in the AID

The solid set was the most common sprinkler irrigation system (2566 ha) in the AID. The irrigation management and farmer behaviours were studied from telecontrol data in 2011. A total of 26,388 hydrant valve irrigations events and 136,296 block valve irrigations events were analysed during the 2011 irrigation season (from April to September). The number of irrigation blocks per hydrant varies depending on the hydrant area and on the hydrant inflow-rate. Figure V.4 presents the number of irrigated blocks per hydrant and the correspondent percentage of the area in the AID. The average area of a hydrant in the AID was 12.5 ha. The 53% of the total solid-set area (corresponding to 100 hydrants) was arranged in hydrants with 8 to 10 irrigated blocks. The 22% of the area (corresponding to 80 hydrants) was arranged in hydrants with 6 to 8 irrigation blocks. The 23% of the area was arranged in small hydrants with less than 6 irrigated blocks. Only four hydrants have more than 10 irrigated blocks and correspond to 5% of the total irrigated area. The land consolidation in the AID promoted bigger plots, farms and hydrant irrigated area. It is important to considerer the hydrant size and its inflow rate since it determines the flexibility to manage energy cost and meteorological constrains (Zapata et al., 2007).

The hydrant flow rates in the AID vary from 18 to 100 L s^{-1}, depending on the irrigated area. Hydrant irrigated area lower than 9 ha have a flow rate of 18 L s^{-1} which ensures the hydrant design criterion of 2.0 L s^{-1} ha^{-1}. There are exceptions to this rule, represented by maximum values of 31 L s^{-1} ha^{-1} (small hydrant irrigated area) and occasional minimum values of 0.5 L s^{-1} ha^{-1}.

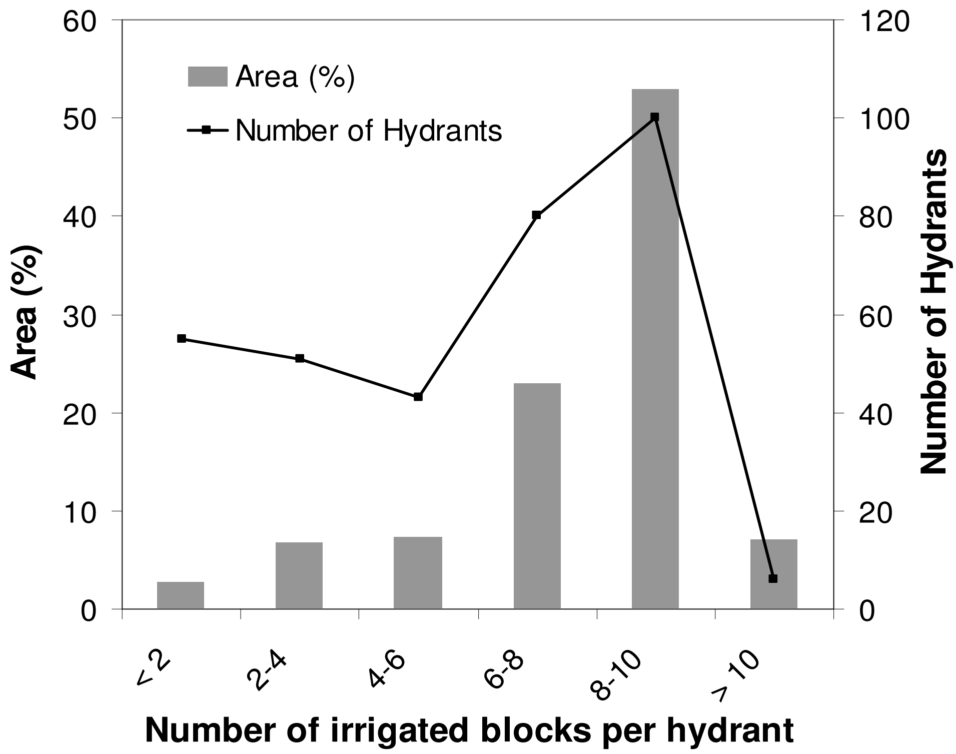


Figure V. 4. *Irrigated area (in % of the total irrigated area) and number of hydrants in relation with the number of irrigated blocks per hydrant in the Almudevar irrigation district.*

Table V.6 presents the general information and data collected in the ten supervised plots in 2010 irrigation season obtained from the pressure transducer measurements. Average irrigation pressure for the ten supervised IB of the ten plots in all irrigation events varied from 305 kPa to 420 kPa. The lowest irrigation pressures were adequate for the current triangular sprinkler layout (T18x18). On the other hand, the largest irrigation pressures were excessively high and self-defeating in windy areas. Low intra-irrigation pressure variations for the ten studied plots were detected (from 0.7% to 7.7%) indicating an adequate network irrigation design. Pressure variation between irrigation events resulted high in plots number 2 and 7 with CV values of 16.9% and 18.6%, respectively, and moderate or low in the other eight monitorized plots, indicating that the seasonal variation in the collective network demand moderately affects the hydrodynamics of the on-farm network. Daytime irrigation for the supervised IB was lower than 20% of the total irrigation time for 8 over 10 plots Preferences for daytime or nighttime irrigation indicated that the block irrigation sequence of the plots was not periodically modified.

Irrigation schedules based on nighttime irrigation should be frequent in the Ebro Valley region because the night-time wind drift evaporation losses (WDEL) in solid set is one-half of daytime losses (Playán et al. 2005) and also because of the cheapest night-time electric tariffs. In plots 1 and 7 (Table V. 6), the irrigation time was uniformly divided between the day and night. This type of irrigation pattern requires periodic changes in the irrigation schedule but is more efficient than fixed block sequence irrigation, according to Dechmi et al. (2004). Irrigation time per block varied between 1.0 h and 3.2 h and irrigation frequency varied between 1.1 to 2.7 days, for the maize crop. Differences in irrigation time per event between plots of the same crop were typically accompanied by differences in intervals between irrigation events. For a specific monitored plot, the irrigation time per block showed high variability along the season (Table V. 6).

Table V.6. *Pressure transducer data analysis for the ten supervised plots in 2010. For each plot the crop, area, averaged irrigation pressure and variation coefficient between irrigations and intra-irrigation, percentage of daytime irrigation, irrigation frequency, average and variation coefficient of irrigation time per block and event and were presented. Values in parentheses represent the coefficient of variation.*

Monitored plot	Crop	Plot Area (ha)	Shared hydrant	Irrigation pressure			Irrigation time		
				Average value	CV % intra-irrigation	CV % between irrigations	Daytime irrigation (%)	Days between irrigations	Irrigation time (h block^{-1} event^{-1})
1	Alfalfa	26.2	Yes	389	7.7	4.7	46.9	1.9	1.8 (47)
2	Maize	4.3	Yes	336	7.4	16.9	0.3	1.1	1.0 (14)
3	Maize	3.5	Yes	379	0.9	2.1	0.0	1.1	1.4 (32)
4	Maize	1.2	Yes	370	7.6	9.9	5.8	2.7	2.7 (21)
5	Maize	24.3	No	360	1.7	6.5	10.5	1.5	3.2 (38)
6	Maize	16.8	Yes	330	4.5	1.7	1.8	1.8	1.9 (24)
7	Rice	13.9	No	420	2.7	18.6	54.2	1.4	1.6 (40)
8	Alfalfa	13.2	No	305	1.2	4.2	0.0	1.3	1.6 (42)
9	Sunflower	23.8	No	343	4.8	11.4	0.0	1.9	1.1 (41)
10	Barley-Sunflower	7.4	No	361	2.2	10.8	19.0	1.8	1.8 (53)

Table V. 7 presents a summary of irrigation times and depths obtained from the telecontrol data acquisition system for the 2011 irrigation season. The schedules were analysed accounting for differences between crops and hydrant size (number of IB). The area (%), the seasonal irrigation time per IB (h), the seasonal applied irrigation dose (m^3 ha-1), the irrigation time per event (h) and the irrigation frequency (days) were analyzed.

Significant effect of the number of IB per hydrant in the seasonal irrigation dose applied in the different crops was found. In alfalfa the seasonal irrigation dose increases with the number of IB. However, the opposite was found in maize. In barley, plots with 8-10 blocks used about double irrigation dose than the other plots with lower number of blocks. No significant differences were found for the double cropping vetch/maize and barley/maize.

The irrigation time per event (h) and the irrigation frequency (time between consecutive irrigation events, in days) were analysed in two different periods, from May to June and from July to August. As a general trend, the irrigation time per event slightly increased from May-June to July-August while the irrigation frequency clearly decreased. The trend follows the crop irrigation requirements. An increase on applied irrigation depth with the number of IB per hydrant was observed for alfalfa and barley, since a decrease was observed for maize and the double crop ray-grass/maize (only one plot). The particular schedule of maize irrigation requirements that concentrates high demand in a short period of time can be limited by the irrigation time availability of the hydrant with large number of IB, resulting in a significant decrease on applied irrigation dose. This conclusion was also obtained from the comparison between $SIPI_{July}$ values for corn for hydrants composed with less than 8 IB or with more than 8 IB, presented in Table V. 5.

Table V.7. *Summary of irrigation scheduling results for major crops and block number per plot in the solid set systems of the Almudevar Irrigation District in 2011: Area (%), Seasonal irrigation time per IB (h), Seasonal irrigation dose (m^3 ha^{-1}), irrigation time per IB and event (h) and interval between irrigations (days) for May to June and from July to August. The extreme values of irrigation time per IB and interval between irrigations were excluded in these analyses. Duncan's multiple comparison procedure was performed to characterize factors affecting the seasonal irrigation time per IB and the irrigation dose.*

Crop	Number of irrigated blocks	Area (%)	Seasonal irrigation time per IB (h)	Seasonal irrigation dose (m^3 ha^{-1})	Irrigation time per IB (h $event^{-1}$)		Irrigation frequency (days)	
					May-June	Jul-August	May-June	Jul-August
Alfalfa	≤6	5.3	130^a (23)	8298^a	1.74	1.67	3.45	1.56
	6 - 8	22.4	161^b (20)	9165^b	1.13	1.41	1.93	1.47
	8 - 10	72.2	178^c (34)	9886^c	1.44	1.50	1.63	1.58
Maize	≤6	21.4	147^a (19)	8648^a	1.17	1.65	3.63	1.10
	6 - 8	31.0	140^b (13)	7769^b	1.14	1.55	2.05	1.14
	8 - 10	47.6	135^b (19)	7361^b	1.03	1.20	1.69	1.20
Barley	≤6	21.4	17^a (126)	1100^a	1.59	-	18.78	-
	6 - 8	34.3	16^a (60)	1023^a	1.68	-	22.70	-
	8 - 10	44.4	27^b (64)	1944^b	1.08	-	18.80	-
Rye Grass/Maize	≤6	22.4	146^a (18)	8825^a	1.15	1.47	1.74	1.02
	6 - 8	24.8	130^a (23)	7569^a	0.98	1.48	2.06	1.93
	8 - 10	45.1	157^a (17)	8856^a	1.03	1.37	1.73	1.09
	> 10	7.6	118^b (0)	6117^b	1.62	0.99	1.85	0.89
Vetch/Maize	≤6	16.0	141^a (18)	7747^a	1.24	1.65	1.68	1.26
	6 - 8	29.5	147^a (26)	8255^a	1.03	1.42	1.50	1.13
	8 - 10	54.4	158^a (11)	8634^a	1.03	1.60	1.45	1.31
Barley/Maize	≤6	31.3	142^a (37)	7012^a	1.23	1.50	3.03	1.12
	6 - 8	11.6	132^a (40)	6577^a	0.98	1.62	2.13	1.09
	8 - 10	57.2	134^a (36)	6698^a	0.99	1.20	2.81	1.52

a, b and c,: $P < 0.01$

The irrigation scheduling patterns of all the irrigation events applied in 2011 were summarized in Figure V.5. Figure V.5.a presents for each hour of the day its frequency as irrigation starting time. The most frequent (30%) irrigation starting time is the first hour of the day; also the hours between the 19:00 and the 23:00 were frequent. Farmers are thus aware of the advantages of night-time irrigation due to lower wind drift and evaporation losses and also due to energy prices (cheaper at the night, Figure V.7.a). A clear decrease in irrigation starting time could be observed at the central hours of the day, reaching minimum values between 10:00 and 16:00 hours. Hydrant irrigation starting time increased along the evening, typically reaching a first peak in the early night hours (19:00–22:00) and a maximum peak at 0:00. These results agree with data presented by Salvador et al. (2011) for a sprinkler irrigation district in the Ebro Valley and differ from results presented by Khadra and Lamaddalena (2010) in Bari (southern Italy), where peak irrigation water use were recorded at the central hours of the day (from 9:00 to 17:00). In this study, crops were generally olive trees and vegetable crops under drip irrigation. Differences in the irrigation system explain the opposite daily water use patterns in both areas, since drip irrigation performance is largely independent of meteorology and needs lower irrigation flows and then lower energy demands.

The IBs of a plot are sequentially irrigated during an irrigation event. The sequence can be maintained or changed during the season. Figure V.5.b presents the frequency of changes in the IBs sequences of the plots in 2011. The 77.4% of the plots do not change the IBs sequence along the season (constant sequence) and the rest varies the IBs sequence. Figure V. 5.c presents the variation of irrigation starting time for the plots that maintain constant the IBs sequence. The Figure showed that the irrigation starting time was conserved in 38%, 44% and 41% of the plots in April, May and the first half of June respectively. From the second half of June to the end of August (the period with large irrigation water requirements) most of the plots change the irrigation starting time. When the IBs sequence, the starting irrigation time and the irrigation time remains constant each IB irrigates always at the same time of the day and presumably with homogeneous meteorological conditions The wind speed and the relative humidity in the Ebro Valley present a clear pattern of variability along the day (Martinez-Cob et al., 2010), with high wind speed and evaporative demand on the central hours of the day and low wind speed and evaporative demand on the nigh time. This irrigation pattern promotes differences on water application depth and variability on crop yield between IB of the same plot.

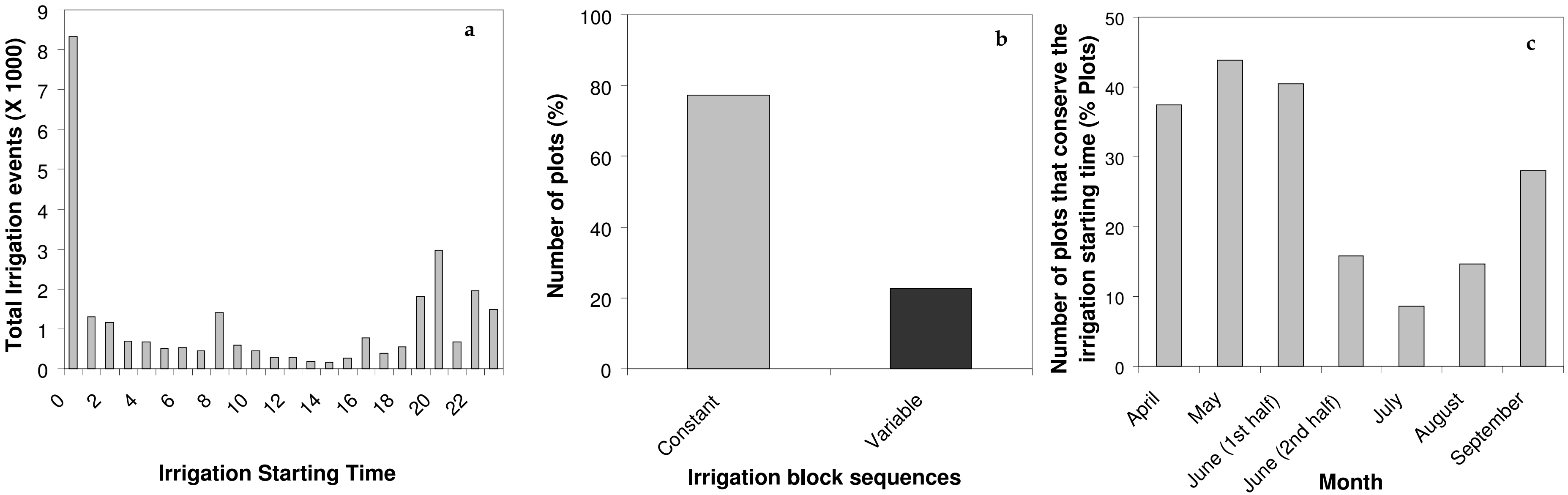


Figure V.5. *Histogram of starting irrigation time (hour of the day) for all hydrants irrigation events during 2011 irrigation seasons (a). Number of plots, expressed in percentage of the total, that maintain constant or variable the irrigation block sequence along the 2011 season (b). Number of plots that maintain both the irrigation block sequence and the irrigation starting time, expressed in % of the total number of plots, during the 2011 irrigation season (April-September)(c).*

Meteorological conditions affect the sprinkler irrigation performance, both the wind drift and evaporation losses (WDEL) and the irrigation uniformity (Keller and Bliesner 1990; Tarjuelo et al., 2000; Playán et al., 2005; Zapata et al, 2009; Sanchez et al., 2010). Significant water losses were reported in sprinkler irrigation, particularly in areas with strong winds and high evaporative demand (Playán et al., 2005). The most cited meteorological variables affecting WDEL are wind speed (U), air temperature (T), relative humidity (RH) and vapour pressure deficit (VPD) (Tarjuelo et al., 2000). Wind speed has often been documented as the most significant meteorological variable affecting WDEL. Figure V.6 presented daily evolution of irrigation volume applied in the AID, daily evolution of wind speed and precipitation. A decrease in irrigation consumption was detected before and following medium to large precipitation events. The effect of precipitation on irrigation scheduling is clear. A precipitation event of more than 10 mm day^{-1} generates a daily decrease in irrigation consumption to less than half. Medium to high wind speed (>3 m s^{-1}) decrease significantly the daily irrigation consumption. Special consumption patterns were observed during the weekend (peaks in Figure V.6) with a significant increase in water demand independently on meteorological conditions and largely dependent on energy prices (during the weekend operates the cheapest energy tariff, P6, Figure V.7.a).

The effect of wind speed, temperature and relative humidity on applied irrigation volume was statistically analysed using semi-hourly values. Non-parametric correlations were used, determining Spearman's Rho (r_s). Regarding wind speed, correlation analyses were performed from May to September. For all the months the correlation was significant ($P<0.01$) and negative (average r_s of -0.063). The analogous analyses for temperature and relative humidity showed similar results. Significant and negative correlations were found in the 100 % of semi-hourly data analysed for air relative humidity (average r_s of -0.041) and significant and positive correlations were obtained for air temperature (average r_s coefficients of 0.095).

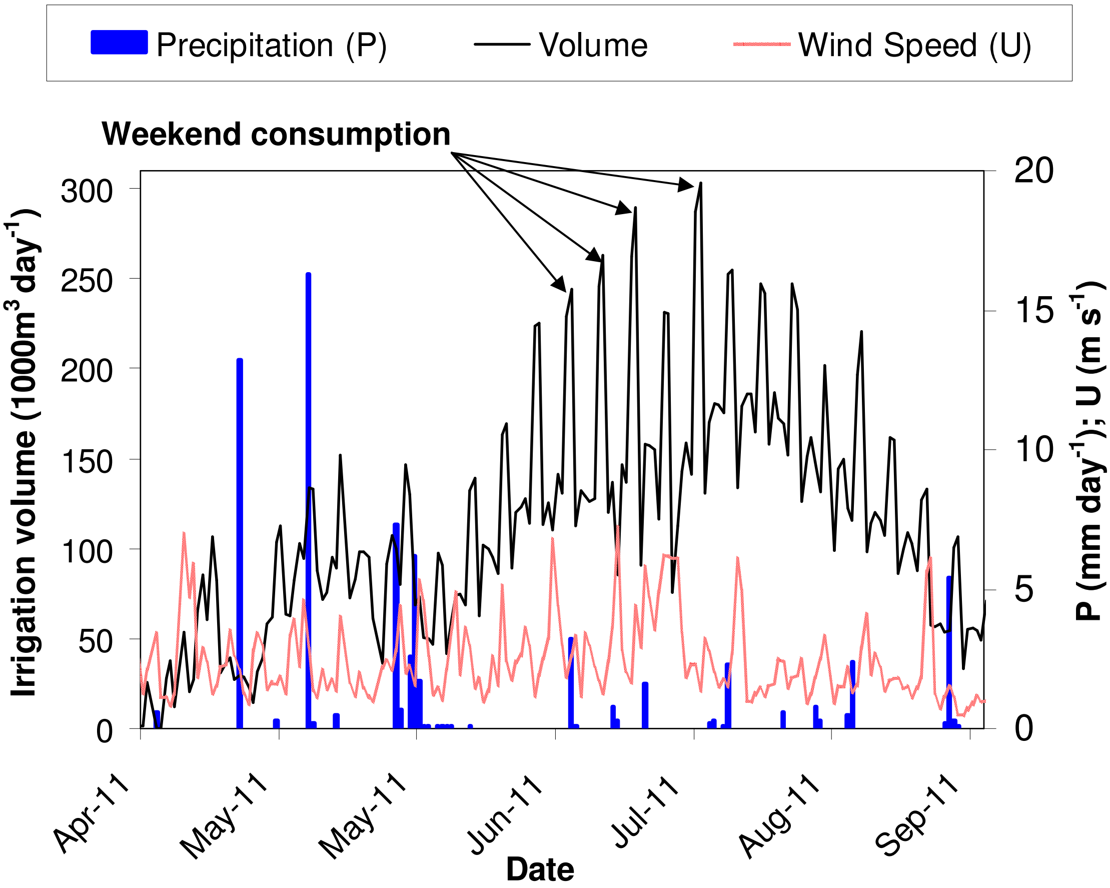


Figure V.6. *Daily irrigation water consumption (Irrigation volume, m3), precipitation (P, mm day^{-1}) and average wind speed (U, m s^{-1}) along the 2011 irrigation season (April-September) in the Almudevar Irrigation District.*

In general, all the correlations presented between the semi-hourly irrigation volume and meteorological data were significant (P< 0.01), even that, the Spearman Rho coefficients (r_s) were low compared to those presented by Salvador et al. (2011) for a sprinkler irrigation district in the Ebro Valley, due to the lack of immediate reaction to the meteorological changes determined by the on-demand ordering (farmers order the irrigation water two days in advance and cannot cancel their orders).

The farms survey of crop yields performed in the 2011 season in the AID (Jimenez-Aguirre and Isidoro, 2012) provides average yields of 13,500 kg ha^{-1}, 14,410 kg ha^{-1}, 13,086 kg ha^{-1}, 2,300 kg ha^{-1}, 5,375 kg ha^{-1} and 5,575 kg ha^{-1} for alfalfa, maize (long-cycle), maize (short-cycle), sunflower, barley and wheat, respectively. Yields obtained in the AID during the 2011 irrigation season were very similar to those obtained in other sprinkler irrigated area of the Aragon Autonomous Community (M.A.A.M.A, 2012). Before the modernization process, the AID had inadequate irrigation distribution and delivery systems, and irrigation management was poor (large irrigation intervals, large delay times in water delivery, and marginal areas with deficit irrigation) (Faci et al., 2000). Barros et al. (2012) reported that crop water-stress occurred widespread in the AID before the modernization and crop yields were lower than optimum and reported yield data of 12,200 kg ha^{-1}, 10,400 kg ha^{-1}, 4,500 kg ha^{-1}, and 6,600 kg, for alfalfa, maize (long-cycle), barley and wheat for the 2006-2008 periods. In general, an important yield increase was observed for maize, a moderate yield increase for barley and alfalfa and a yield decrease for wheat. There is only one year of available data for the post modernized AID, therefore the comparison between crop yields before and after AID modernization should be taken carefully. Crops like maize, barley and alfalfa have taken advantage of sprinkler irrigation management, reducing the crop water stress periods as reported the SIPI analysis or other crop stresses (not analysed). On the other hand, wheat irrigation management by sprinkling requires special attention. Wheat is very sensitive to fungus diseases that are promoted by high air humidity (that increases during sprinkler irrigation) and high air temperatures (common during summer). Irrigation management practices on wheat should avoid create adequate ambient conditions for fungus diseases development.

Figure V.7 presents the farmer irrigation patterns related with the energy tariff period's structure. Figure V.7.a presents the hourly structure of the energy tariff periods for agricultural use only from April to September. The cheapest energy period (P6) has a cost 225% lower than the most expensive energy period (P1). The cheapest energy period was operative during all nighttime periods from 0 to 8, the entire weekend (Saturday and Sunday), National Festive days and all August. The most expensive energy period was only operative during the second half of June and July in daytime period from 11:00 to 18:00. The others energy periods were distributed unevenly during the studied months as mentioned in Figure V.7.a. Figure V.7.b presents the monthly percentage for each energy period of the performed irrigation hours along 2011 in the AID. In all the studied months, most of the irrigation time was performed at the P6 period (from 77 % in April to 100% in August).

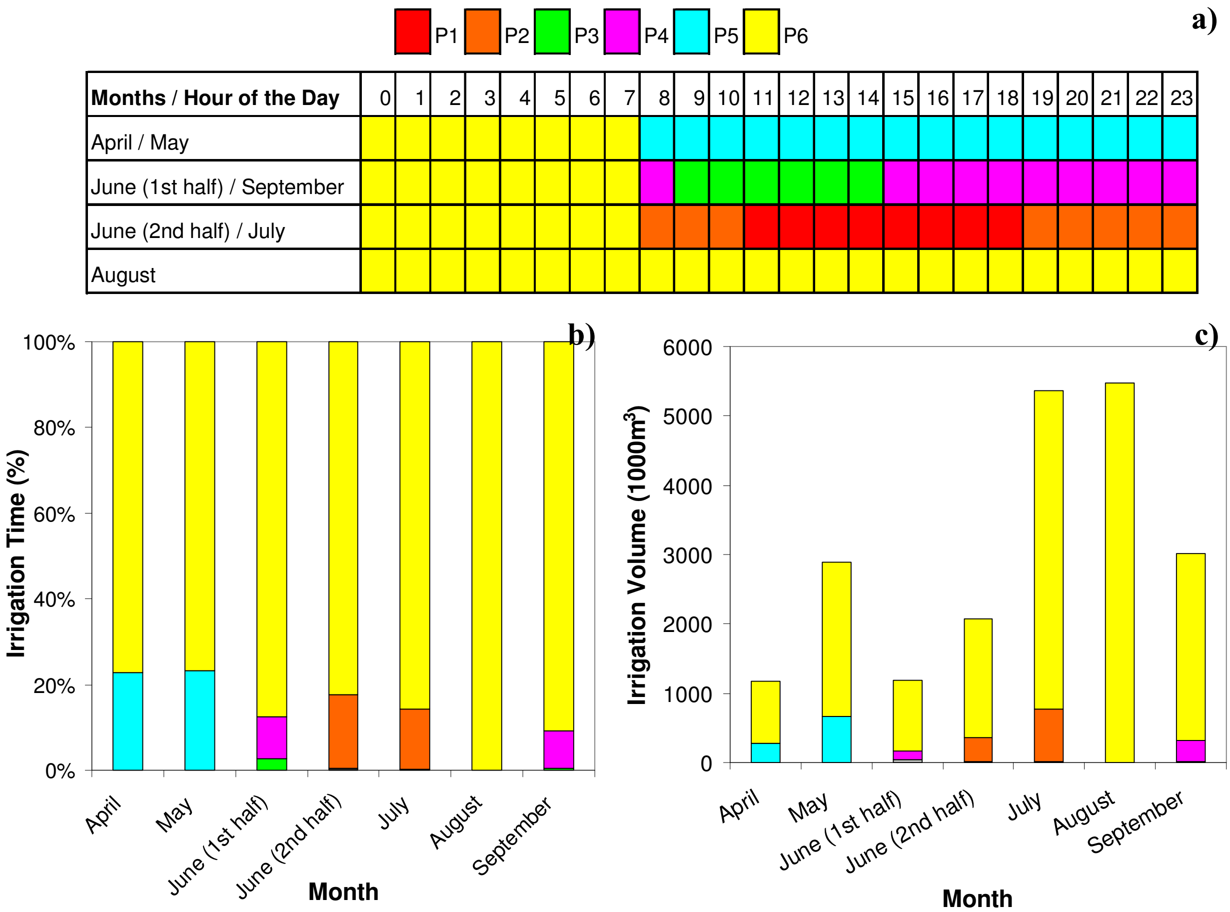


Figure V.7. *Hourly distribution of the six electricity rates for agricultural use during the different months of the irrigation season (April to September) (a). Monthly distribution of irrigation time (%) for each of the six electricity rate periods (b). Monthly distribution of the water volume pumped (x1000 m³) in each of the six electricity rate periods (c).*

Approximately 23% of the irrigation hours in April and May occur during the P5 period (the second cheapest). In the second half of June and over all in July, the available time of the cheapest period (from 0 to 8) was not enough to satisfy crop irrigation requirements and part of the irrigation should be performed on the second most expensive energy period (P2). The 17% and 14% of the monthly irrigation time in the second half of June and July, respectively were performed on the P2 period. The 9% of irrigation time during the first half of June and September were performed on the P4 period. Just a few irrigation hours were performed on the P3 and P1 periods. Figure V.7.c presents the monthly irrigation volume applied at the different energy period. The largest irrigation volumes applied correspond to the moths with highest irrigation requirements, July and August, and the distribution of the volumes between periods is clearly oriented to the cheapest ones. As commented before, during the second half of June and the entire July, the short P6 period was not enough to apply the crop irrigation requirements to all the AID and part of the irrigation should be performed on the second most expensive energy period (P2).

V.3.5. Analysis of AID contracted energy power

The estimated ratios of energy consumption versus pumped irrigation volume for the four irrigated zones were presented on Table V.8. For this study the ratio for each irrigated zone was considered constant for the whole season although its value varies with time depending on the system status (number of operating hydrants, distances and elevation between the pump and the open hydrants and efficiency of the pumps). With these ratios the evolution of the water demand has been translated to energy demand. The largest ratio was found for Matilero (309 KWh $1000m^{-3}$) and the lowest for Colladas (264 KWh $1000m^{-3}$). Differences were not related with the pressure head requirements at the pumping station since Abariés had the largest one (79 m) and Matilero and Colladas had the same (72 m). Differences in pumping efficiency or irrigation patterns can explain the differences.

The evolution in time of the energy demand has been analysed for the four irrigated zones independently and for the months of July (because of its high crop irrigation requirements and its energy cost constrains) and August. Figure V.8 shows for each day of the week on July 2011, the average hourly energy demand (KWh) at the zones of Artical-Violada (Figure V.8.a), Abariés (Figure V.8.b), Matilero (Figure V.8.c) and Colladas (Figure V.8.d). The dashed line presents the maximum contracted power at each energy period. It has to be noted that during the weekend (Saturday and Sunday) the cheapest energy period (P6) operates during the whole day.

Table V.8. *Total energy (KWh) and water consumption (m^3) for the four irrigated zones of the Almudevar Irrigation District (AID). The average ratios of energy consumption versus water consumption (KWh $1000m^{-3}$) are also presented.*

Irrigated zones	Total Energy Consumption (KWh)	Total Water Consumption (m^3)	Ratio Energy: Water (KWh $1000m^{-3}$)
Abariés	2,151,879	7,482,000	288
Artical-Violada	2,645,282	9,571,000	276
Colladas	621,021	2,353,000	264
Matilero	639,044	2,065,000	309
Total	6,057,226	21,471,000	282

In July, month with three different tariffs (P1, P2 and P6, Figure V.7.a), the energy demand shows a significant effort to guide water consumption to the cheapest rate hours (P6, night hours and weekends). The intensive irrigation during the weekend makes that in early Mondays´ hours the water and energy demand considerable decreases compared with the other days of the week. On the other hand, during Thursdays´ nighttime hours, water and energy demand are maximum. This pattern was observed in all the irrigated zones. A more homogeneous distribution of irrigation application along the week can improve the energy management and its cost. In order to analyse penalties for power demand exceeding power contracted, for the four irrigated zones and for each day of the week on July 2011, the maximum hourly energy demand (KWh) was presented in Figure V.9. Results showed that generally the energy demand did not exceed the power contract, except in the P1 period (central hours of the day), especially at the Artical-Violada and Matilero zones. Also, the results point out that the contracted powers for some energy tariff periods are over-estimated during 2011. This excess in power contracted was especially important for the P2 tariff period not only for its high cost but because the type of power contract requires that P1 ≤ P2 ≤ P3 ... ≤ P6. Since the P3, P4 and P5 tariff periods appear only in the months of low water demand, reduction in P2 contracted power allows reduction in power contracted for periods P3, P4 and P5. This adjustment in hiring power in different periods will significantly reduce the power fixed cost.

In August average (Figures V.10 a, b, c and d) and maximum (Figures V.11. a, b, c and d) hourly energy demands show interesting patterns. In this month all the time operates at the cheapest energy tariff period, P6, however, water demand in the central hours of the labour days decrease significantly. However, this behaviour is not detected at the weekend days, where hourly water demand is very homogeneous during all day (as in the rest of weekends of previous months with also the P6 tariff operating). Reduction on irrigation water demand in the central hours of the labour days can be due to the largest wind drift and evaporation losses in this period. The routine established in previous months, or because many farmers at the AID practice part-time agricultural activities and during the weekend part-time farmers like to check that their system is irrigating can explain the irrigation patterns of August.

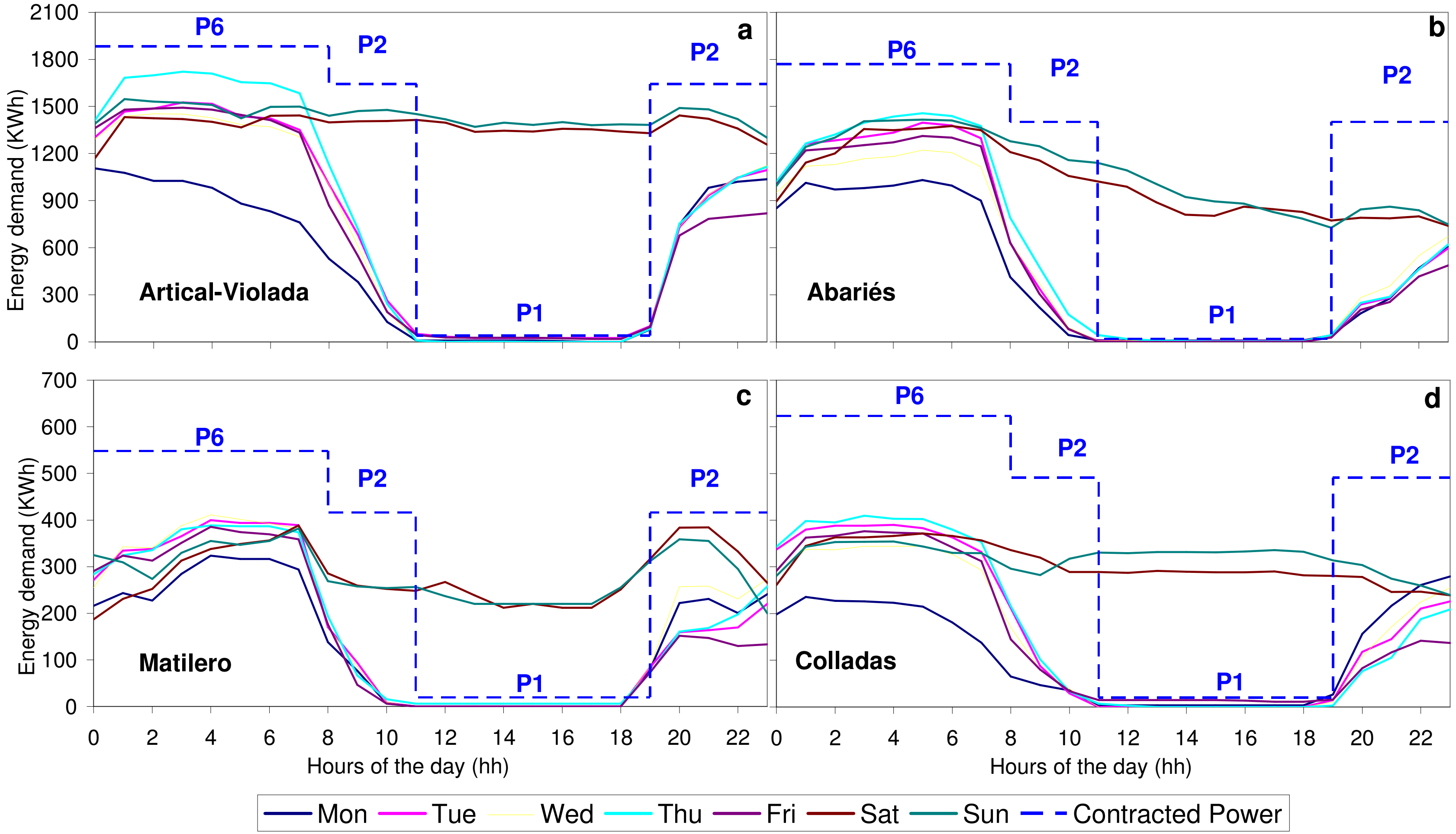


Figure V.8. *Average energy demand (KWh) for each day of the week at the four irrigation zones of the Almudevar Irrigation District in July. Dashed line presents the maximum contracted power at each electricity tariff.*

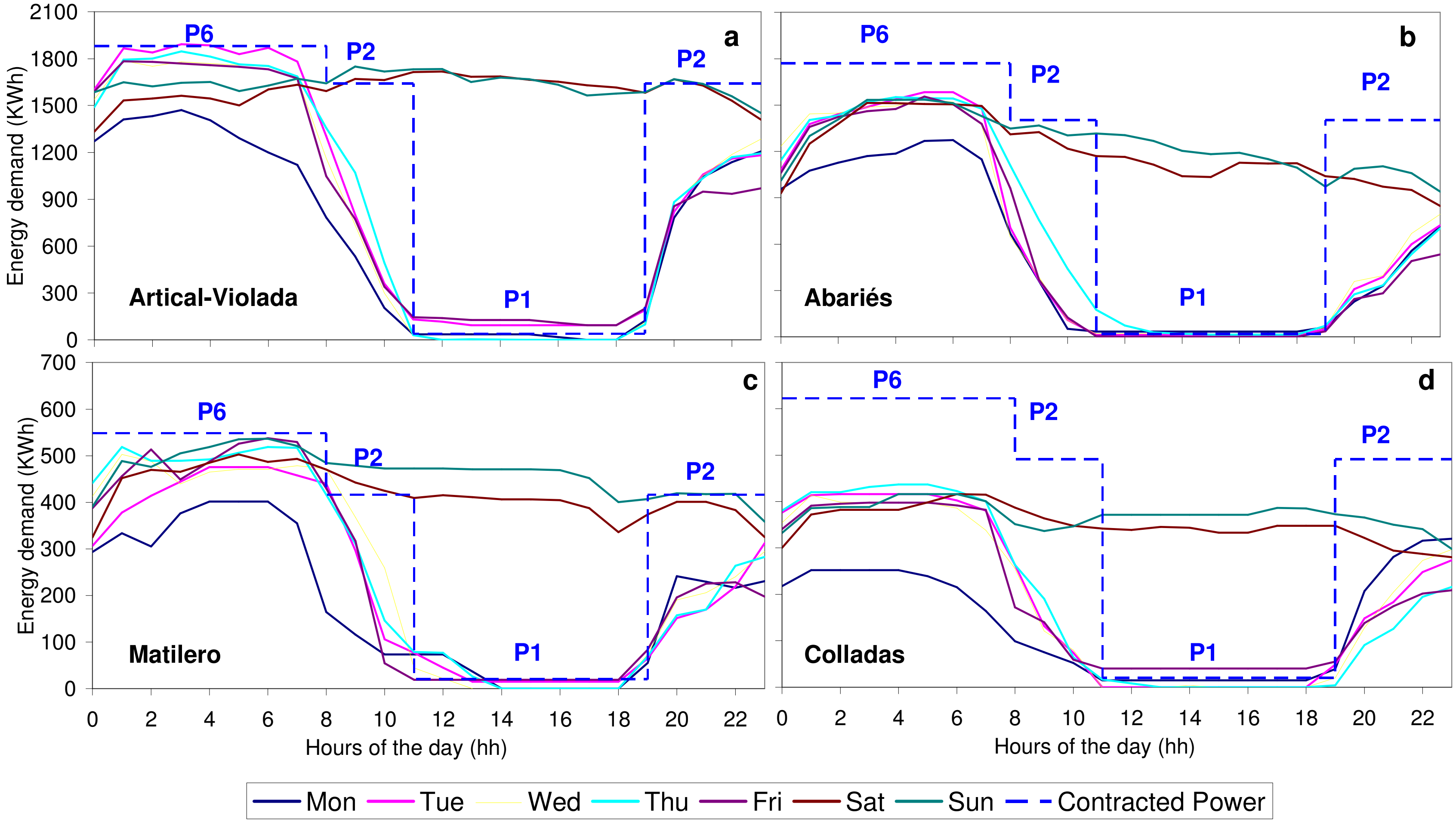


Figure V.9. *Maximum energy demand (KWh) for each day of the week at the four irrigation zones of the Almudevar Irrigation District in July. Dashed line presents the maximum contracted power at each electricity tariff.*

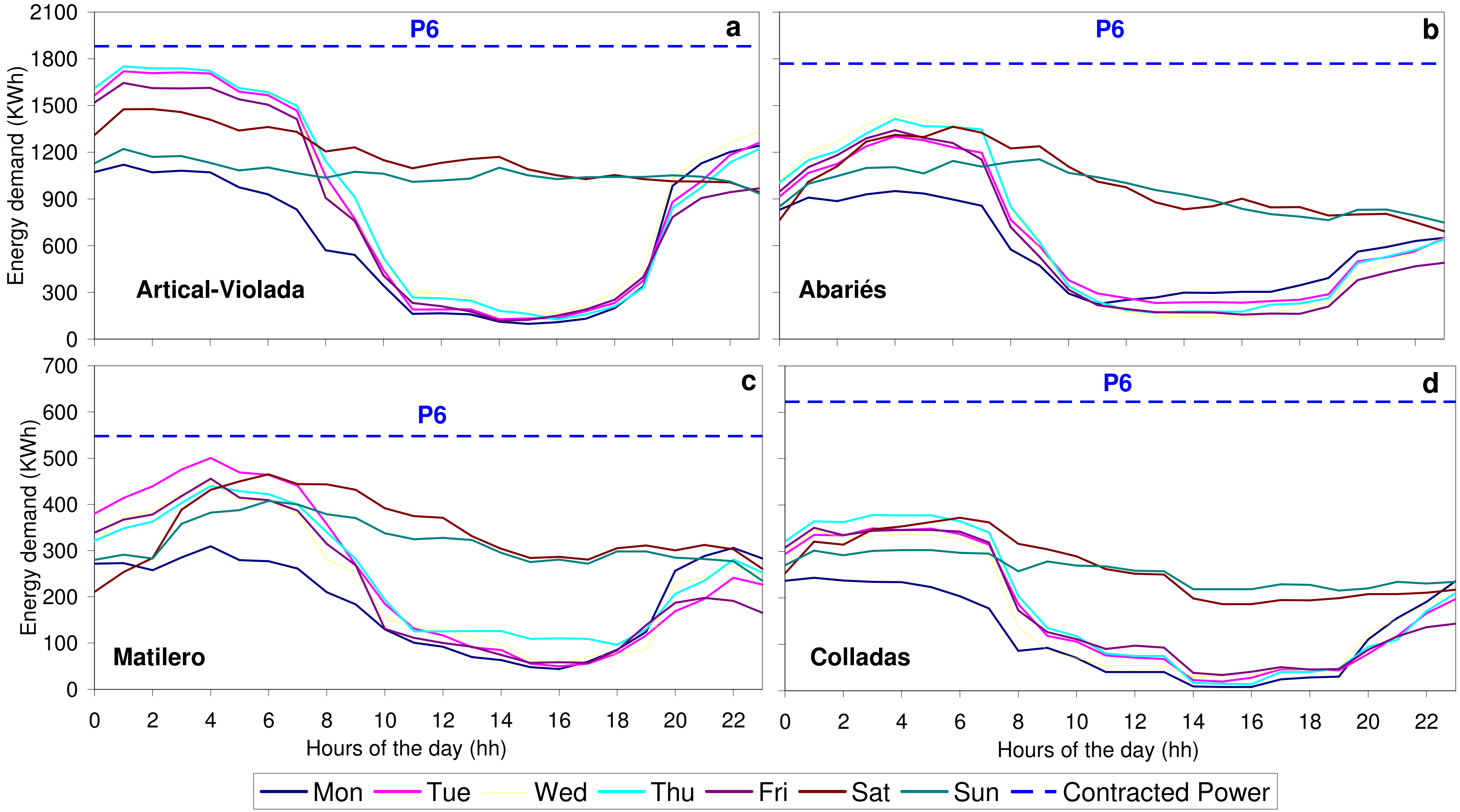


Figure V.10. *Average energy demand (KWh) for each day of the week at the four irrigation zones of the Almudevar Irrigation District in August. Dashed line presents the maximum contracted power at each electricity tariff.*

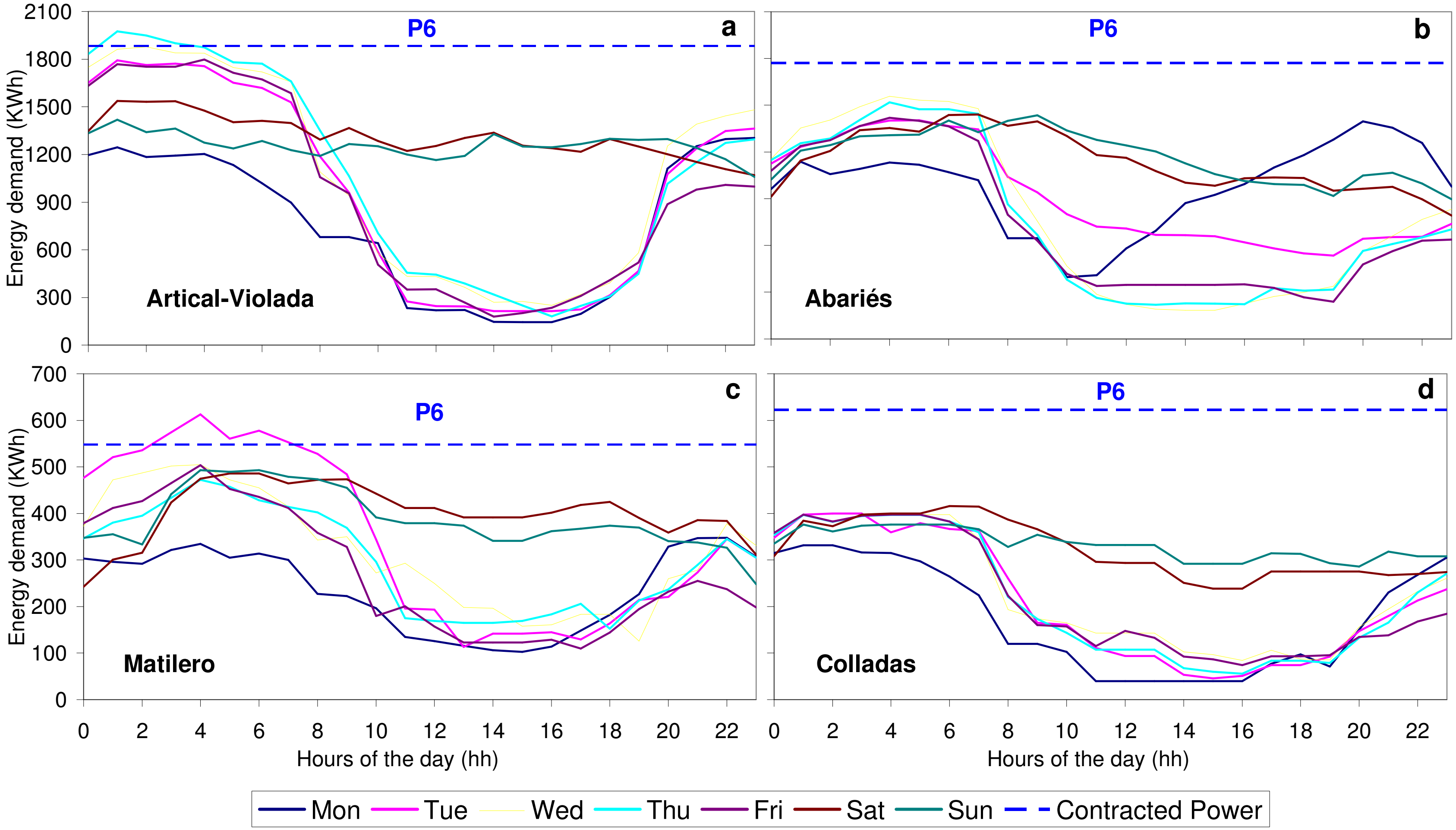


Figure V.11. *Maximum energy demand (KWh) for each day of the week at the four irrigation zones of the Almudevar Irrigation District in August. Dashed line presents the maximum contracted power at each electricity tariff.*

Table V. 9 shows the power contract analysis at the current AID situation and for a proposed scenario for the four irrigation zones. The same volume of current water pumped was assumed for the proposed scenario. The proposed scenario was based on adjusting the contract power at each period to the average consumption and on reducing the penalties for exceeding contracted power. Total power cost for the current situation represents between 25% of total electricity cost for Matilero zone to 30.5% for Colladas zone. These percentages were reduced in the proposed scenario and represent between 17.6% for the Abariés zone to 23% for Colladas zone, of the total electricity cost. The proposed scenario of power contracting resulted in a decrease of 8.4% in the total electricity cost.

In the current situation the electricity costs per volumetric unit was different between irrigated zones, resulting much higher in Matilero (26.6 € 1000 m^{-3}) than in the other irrigated zones. The lowest electricity cost corresponds to Abariés zone (20.8 € 1000 m^{-3}) with the larger established pumping pressure head (79 m, Table V. 2). The differences between irrigated zones were also observed in the proposed scenario since only changes in power contract were considered. The important cost differences between Matilero and the others irrigated zones should be analysed because all the irrigated zones are quite similar in crop patterns and pumping heads and this difference was not expected. The revision of the irrigation patterns (controlling water application during the P1 tariff period) and the analysis of the pumping efficiency should be performed.

Yearly, even without knowledge of the crop pattern, the AID manager face the decision of how much power contract at any tariff period. The analyses and results presented in this work is a valuable tool for the manager to make an adequate decision. The analysis should be performed in successive seasons to provide consistent results.

Table V.9. *Electricity cost analysis for the pumping stations of the four irrigated zones of the Almudevar Irrigation District for the current situation and for a proposed scenario (Scenario 1) with new values of the power contracted in each tariff period. Power cost, penalty cost for exceeding contracted power, total power cost, total electricity cost and average electricity cost per unit of water pumped are presented in the current situation and proposed scenario.*

Scenario	Pumping Station	Power Contracted (KW)						Power Cost (€)	Penalties by Power Exceed (€)	Total Power Cost (€)	Total Electricity Cost (€)	Electricity Cost (€ 1000m^{-3})
		P1	P2	P3	P4	P5	P6					
Current	Abariés	20	1402	1402	1402	1402	1770	42443	470	42914	154836	**20.8**
	Artical-Violada	40	1642	1642	1642	1642	1882	49455	2294	51749	206913	**21.6**
	Colladas	20	491	491	491	491	623	15089	226	15314	50118	**21.3**
	Matilero	20	416	416	416	416	548	12890	661	13551	54887	**26.6**
	Total	100	3951	3951	3951	3951	4823	119877	3651	123528	466754	
Scenario 1	Abariés	30	600	600	600	600	1770	21327	2653	23981	135874	**18.2**
	Artical-Violada	75	1100	1100	1100	1100	1882	35653	3064	38717	194521	**20.3**
	Colladas	30	300	300	300	300	623	10186	148	10335	44845	**19.1**
	Matilero	30	300	300	300	300	548	9978	1122	11100	52241	**25.3**
	Total	165	2300	2300	2300	2300	4823	77145	6988	84132	427481	

V.4. CONCLUSIONS

Irrigation modernization has greatly changed the land structure (tenure and management units) in the AID. The possibilities of the pressurized irrigation systems and the need to amortize them have promoted large area under crops with higher economic margins or double cropping, that in general have increased (around 18%) the net crop irrigation requirements. On the other hand, the new irrigation system has improved the irrigation efficiency and has decreased the average irrigation depth (around 10%). The comparison should be taken carefully since there is only a year of data for the post modernized situation. Also, the average SIPI has changed from 70% for the pre modernized district to 94% for the post modernized district.

The spatial variability of SIPI index at the beginning of the crop season was generally high (except for maize and sunflower), and could be attributed to variability in farmer's irrigation management during this period of low NIRs. This variability was decreasing in the following months, and during July and August the variability was very low for most of the crops. The central and remote management of the irrigation demands homogenise farmer irrigation patterns. The temporal variation of SIPI analysis has resulted adequate to assess on-farm irrigation performance. SIPI significance is affected by the use of net irrigation requirements instead of actual crop consumptive use. This is a major limitation when comparing crop SIPI under different management schemes or irrigation systems, since crop evapotranspiration is likely to change owing to varying degrees of crop water stress.

The meteorology affects sprinkler irrigation management in the AID as reported the significant correlation between water delivery and precipitation (rs = -0.056), daily average wind speed (r_s = -0.063), air temperature (r_s = 0.095) and relative humidity (r_s = -0.041). While the statistical relationships between them were significant, the correlations were low. Considering that the AID is an on-demand irrigation district, the irrigation water order must be done with anticipation (two days ahead of time). This fact makes difficult to find strong relationships between the irrigation managements and the meteorological variables. A centralized decision of the irrigation order based on real data analysis could promote water use efficiency (Zapata et al., 201X).

The irrigation patterns in the AID are a combination of farmer demands and manager interventions. The large part of the irrigation events (30%) in the AID start at midnight hour. A large part (77.4 %) of the plot irrigation events analysed used a fixed IBs sequence and a fixed starting irrigation time (overall in summer months). These patterns promote water and crop yield variability between IB of the same plot. Generally, the irrigation time per event slightly increased from May-June to July-August while the irrigation frequency clearly decreased. This tendency follows the crop irrigation requirements. In general, adequate irrigation practices were observed in the AID as nighttime irrigation scheduling to reduce wind drift and evaporation losses and water application cost (cheapest energy tariff). However, some improvements were also identified as the needed of periodically change the irrigation timing of the IB composing a plot to reduce water and yield variability.

In all the studied months, most of the irrigation time was performed at the cheapest energy period, P6, (from 77 % in April to 100% in August). In the second half of June and over all in July, the available time of the cheapest period (from 0 to 8) was not enough to satisfy crop irrigation requirements of the AID and part of the irrigation time (17% on the second half of June and 14% on July) should be performed on the second most expensive energy period (P2). The energy demand evolution for the different days of the week showed that the intensive irrigation during the weekend makes that in early Mondays´ hours the water and energy demand considerable decreases and during Thursdays´ nighttime hours increases. This pattern was observed in all the irrigated zones. A more homogeneous distribution of irrigation application along the week can improve the energy management and its cost.

In August (all time corresponds to the P6 period) water demand in the central hours of the labour days decrease significantly but was not the case for the weekend days. The reduction in the labour days can be due to the largest wind drift and evaporation losses in this period of the day. And the non reduction on the weekend days can be explained by the routine established in previous months, or because many farmers at the AID practice part-time agricultural activities and during the weekend they like to check that their system is irrigating.

Yearly, even without knowledge of the crop pattern, the AID manager face the decision of how much power contract at any tariff period. The analysis of the current and a proposed scenario of power contract were performed. The proposed scenario, based on adjusting the contract power to the average consumption and on reducing the penalties for excess, resulted in a decrease of 8.4% in the total electricity cost.

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CHAPTER VI: CONCLUSIONES GENERALES

CONCLUSIONES GENERALES

De los distintos temas tratados sobre el riego por aspersión a lo largo de los capítulos de la presente tesis se puede concluir lo siguiente:

En el capitulo II, se ha estudiado el funcionamiento de un aspersor de impacto con nuevas boquillas de plástico (RC130-BY). La novedad de estas boquillas de plástico es facilitar la tarea de mantenimiento y limpieza de los aspersores. Del estudio del comportamiento radial de este modelo de aspersor se puede concluir que la aplicación del agua en la zona cercana al aspersor (primeros 2 a 6 metros) es menor que la producida por el mismo modelo de aspersor pero con boquilla de latón (RC130-L). Esta diferencia aumenta con la presión de funcionamiento pero disminuye al aumentar el diámetro de la boquilla principal. La comparación de las curvas radiales de los distintos modelos de aspersor mostró que la forma de la misma depende principalmente del tipo y modelo de aspersor. Los resultados de la comparación de la uniformidad de reparto en cobertura entre los dos tipos de aspersores mostraron patrones distintos en función de los niveles de viento. Para vientos moderados ($U \leq 4.0$ m s^{-1}) la uniformidad a la que da lugar los aspersores equipados con boquillas de latón (RC130-L) es mayor que la de los mismos aspersores equipados con las boquillas de plástico. Sin embargo, en condiciones de vientos elevados las diferencias no son relevantes.

En el capitulo III, se han determinado de forma detallada las pérdidas reales de agua que se producen en el riego por aspersión (SEL) sobre un cultivo de alfalfa. Este estudio detallado ha permitido separar la parte de estas pérdidas que disminuyen la evapotranspiración (ET) del cultivo. Las pérdidas brutas por evaporación y arrastre ($WDEL_g$) fueron de media superiores en los riegos diurnos (10,9%) que en los nocturnos (3,7%). Por otro lado, la reducción de la ET durante los riegos diurnos (4.3% del agua total aplicada) fue también superior a la de los riegos nocturnos (0.8% del agua total aplicada). En cuanto a las perdidas por intercepción netas (IL_n), dichas pérdidas también fueron superiores durante los riegos diurnos (3.1%) que durante los nocturnos (2.4%). El computo global de las pérdidas (SEL_n) arroja valores superiores para los riegos diurnos (9.8%) que para los nocturnos (5.4%). Lo mismo ocurre con las pérdidas brutas, sin embargo, las diferencias entre riegos diurnos y nocturnos fueron menores.

La comparación de los resultados de pérdidas en riego por aspersión sobre alfalfa del presente trabajo con los realizados sobre maíz (Martínez-Cob et al., 2008) mostró diferencias en $WDEL_g$ y SEL_n entre ambos cultivos (datos cuantitativos sobre las diferencias). La reducción de la ET durante el riego en el cultivo de alfalfa (42%) resultó inferior a la medida por Martínez-Cob et al. (2008) en maíz (55%), aplicando la misma metodología. Estas diferencias se pueden explicar principalmente por las diferencias en las condiciones meteorológicas de ambos ensayos, por la diferencia de arquitectura entre el maíz y la alfalfa y por la diferencias de mojabilidad entre las hojas de maíz y alfalfa t

En los capítulos IV y V se ha analizado la gestión del riego en dos comunidades de regantes de Aragón a partir de la explotación de la información disponible y la generada a tiempo real por los sistemas de telecontrol y otras medidas directas de variables meteorológicas y manejo del riego en la zona regable.

En el capitulo IV se han analizado las pautas de riego de los agricultores a través de los datos del telecontrol y la monitorización del riego de los sectores hidráulicos en 10 parcelas en la Comunidad de Regantes de Candasnos (CID). Las dosis estacionales medias de riego para los cultivos de maíz de ciclo largo, alfalfa y frutales de hueso fueron 822, 870 y 565 mm, respectivamente. El coeficiente de variación de estas dosis para maíz de ciclo largo, alfalfa y frutales de hueso fue de 22, 17 y 25%, respectivamente. Los promedios del índice estacional de calidad del riego (SIPI) para el maíz, alfalfa, girasol, cebada y melocotonero en la Comunidad de Regantes de Candasnos (CID) fueron de 83%, 131%, 110%,107% y 123%, respectivamente indicando que en la CID los regantes tratan de optimizar el uso del agua mediante la restricción de las aplicaciones en cultivos resistentes a la sequía tal y como el caso de la alfalfa, cebada y girasol, y, limitan el estrés hídrico para los cultivos sensibles (maíz). También se observó una estrategia de riego deficitario en frutales con una reducción continua del agua aplicada para los frutales a lo largo del ciclo de cultivo.

El análisis de la variabilidad temporal del SIPI complementado con el control de la secuencia del riego en fincas seleccionadas ha mostrado ser una herramienta muy útil para mejorar la gestión del riego a nivel de parcela. Esta metodología podría aplicarse fácilmente en cualquier red de riego telecontrolada. Sin embargo, la fiabilidad y la precisión de la metodología de determinación de las necesidades hídricas de los cultivos es un factor clave para la estimación de los índices de calidad de riego, ya que los valores reales de las necesidades hídricas netas afectan directamente los SIPI.

La corta duración media de los riegos por sector en maíz (de entre 1-1.5 horas) y la alta frecuencia incrementa las pérdidas por evaporación e intercepción por el cultivo. En cuanto a los calendarios de riego, se observaron dos pautas diferentes en la CID. La primera se caracterizó por una mínima modificación del calendario de riego y la segunda se caracterizó por los cambios semanales en el calendario de riego. La segunda pauta es la más frecuente para los sistemas de cobertura fija.

La modernización de la Comunidad de Regantes de Almudevar (AID) ha promovido una mayor intensificación de cultivos que ha aumentado (+18%) las necesidades hídricas netas. Por otro lado, los nuevos sistemas de riego han mejorado la eficiencia de riego y se han reducido las dosis aplicadas (-10%). El valor promedio del SIPI ha pasado del 70% antes del proceso de la modernización al 94% después de la modernización. Las pautas de riego en la AID corresponden a una combinación de la demanda de los agricultores e intervenciones de los gestores. En general, las prácticas de riego son adecuadas con una mayoría de riegos nocturnos con objeto de reducir el coste energético del bombeo y las pérdidas por evaporación y arrastre (WDEL). El 30% de los eventos de riego se inician a medianoche. Una gran parte (77,4%) de los eventos de riego analizados utilizaron una secuencia y una hora de inicio de riego fija. Para evitar las mismas condiciones meteorológicas en los sucesivos riegos, se hace necesario cambiar el tiempo de inicio del riego de los sectores de riego que componen una parcela.

En general se ha hecho un buen uso de la energía eléctrica en la AID. En todos los meses estudiados, la mayor parte del tiempo de riego se llevó a cabo en el período de energía más barata (P6), (77% en abril a 100% en agosto). En la segunda quincena de junio y sobre todo en julio, el tiempo disponible del período más barato (8 horas al día) no fue suficiente para satisfacer las necesidades del cultivo de riego de la AID y una parte del tiempo de riego (17% en la segunda quincena de junio y 14% en julio) se realizó en el período de energía más cara (P2).

Se encontró que una distribución más homogénea de la aplicación de riego a lo largo de la semana puede mejorar la gestión de la energía y su coste. Se observa una concentración de los riegos en los fines de semana en las horas centrales del día sobre todo en el mes de Agosto. El patrón de consumo energético del año 2011 en la AID, indica que las potencias contratadas pueden rebajarse, especialmente la potencia contratada en P2. Para asegurar esta afirmación es necesario repetir este análisis en los años siguientes.

Los resultados de esta tesis indican que es preciso continuar con el análisis de las posibilidades que ofrecen los sistemas de telecontrol en el uso del agua y la energía en comunidades de regantes modernas. La amortización de las inversiones de la modernización del regadío supone un nuevo reto para las comunidades de regantes. Es indispensable el seguimiento de los procesos implicados en la gestión del agua de riego y de la energía asociada. La introducción de las pérdidas netas en riego por aspersión en la rutina diaria de las gestión del riego en las comunidades de regantes, lo cual supone la incorporación de los datos meteorológicos y agronómicos de los cultivos a los sistemas de telecontrol o/y en su caso en los programadores de riego en parcela, es un campo de gran interés futuro. También se debe destacar la importancia de los sistemas de telecontrol en la evaluación de la calidad de riego a nivel de sectores de riego en parcela y en la simulación de posibles demandas futuras para un buen manejo de riego en las comunidades de regantes.